THE UNIVERSITY OF ALBERTA

WATER BALANCE PATTERNS - BEAVER CREEK BASIN: ENVIRONMENTAL MANAGEMENT ALTERNATIVES IN SYNCRUDE SITE DEVELOPMENT

by

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A THESIS

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ABSTRACT

The exploration and development of the Athabasca Oil Sands has been stimulated by the increasing demand for fossil fuel in North America. There is general speculation that a number of plants may be constructed by the year 2000 A.D. If many of these plants are to be constructed it will be necessary to modify large tracts of land and withdraw thousands of hectare meters of water for processing purposes. Water balance patterns will be altered and higher yields and flashier runoff regimen will be experienced where land surfaces have been modified. Water management objectives and decisions should be based on knowledge of present and future water balance patterns in an effort to ensure the least damage will be done to the environment and still maintain economic efficiency.

Thornthwaite water balance procedures are used in the thesis in an attempt to define present and future water balance patterns in the Beaver Creek Basin. The study area is located approximately 480 kilometers north northeast of Edmonton. Syncrude Canada Ltd. is constructing an oil sands extraction plant that requires the removal and modification of vegetation from approximately 10,000 hectares of land. Syncrude's policy is to provide on-site disposal by evaporation, of all water used in plant operations as well as all locally generated surpluses. Estimates of future surpluses will greatly aid in planning for disposal. Information on deficiency patterns may be used in irrigation scheduling of revegetated areas. Discussion of expected changes in runoff regimen is included to show when and under what conditions erosion potentials are the

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greatest.

A literature search was conducted in an effort to determine possible applications and results of Thornthwaite water balance procedures in Western Canada. Thornthwaite's method for estimating potential evapotranspiration was compared with that of Penman and for the purposes of this study Thornthwaite's was found to be the more directly applicable. Daily water balance procedures were computed for the 32 year period 1945 through 1976 using meteorological data from Fort McMurray Airport and a summary of the results are presented in the thesis. A comparison of daily and monthly water balance procedures was conducted to determine if more reliable estimates of surplus and deficiency patterns can be obtained using daily data. Estimated surpluses are compared with gauged discharge for the period 1972 through 1976. Estimated surpluses are in close agreement with gauged discharge in the wetter years but adjustments in the water balance procedures are necessary in drier years.

Discharges of streams originating in upland areas were compared with those of lowland streams to show the changes in yield patterns caused by higher elevations. An adjusted water balance equation is presented which is representative of the increased precipitation and decreased potential evapotranspiration in the Thickwood Hills (i.e. headwaters of Beaver Creek Basin).

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percentage increase in yield coming in the drier years. Water management alternatives are suggested which would provide for a reduction in disposal of local surpluses to the tailings ponds as well as provide for enhancement of water quality by snowpack management. Water management alternatives for areas west of the mine and plant site are discussed with many being complementary in objective to both the environment and mining operations.

A better understanding of present and future water balance patterns should allow water resource decision makers to define their objectives more closely. The most desirable water management alternatives can then be implemented in an effort to make the best use of water as a natural resource.

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CHAPTER I

1.1 Introduction

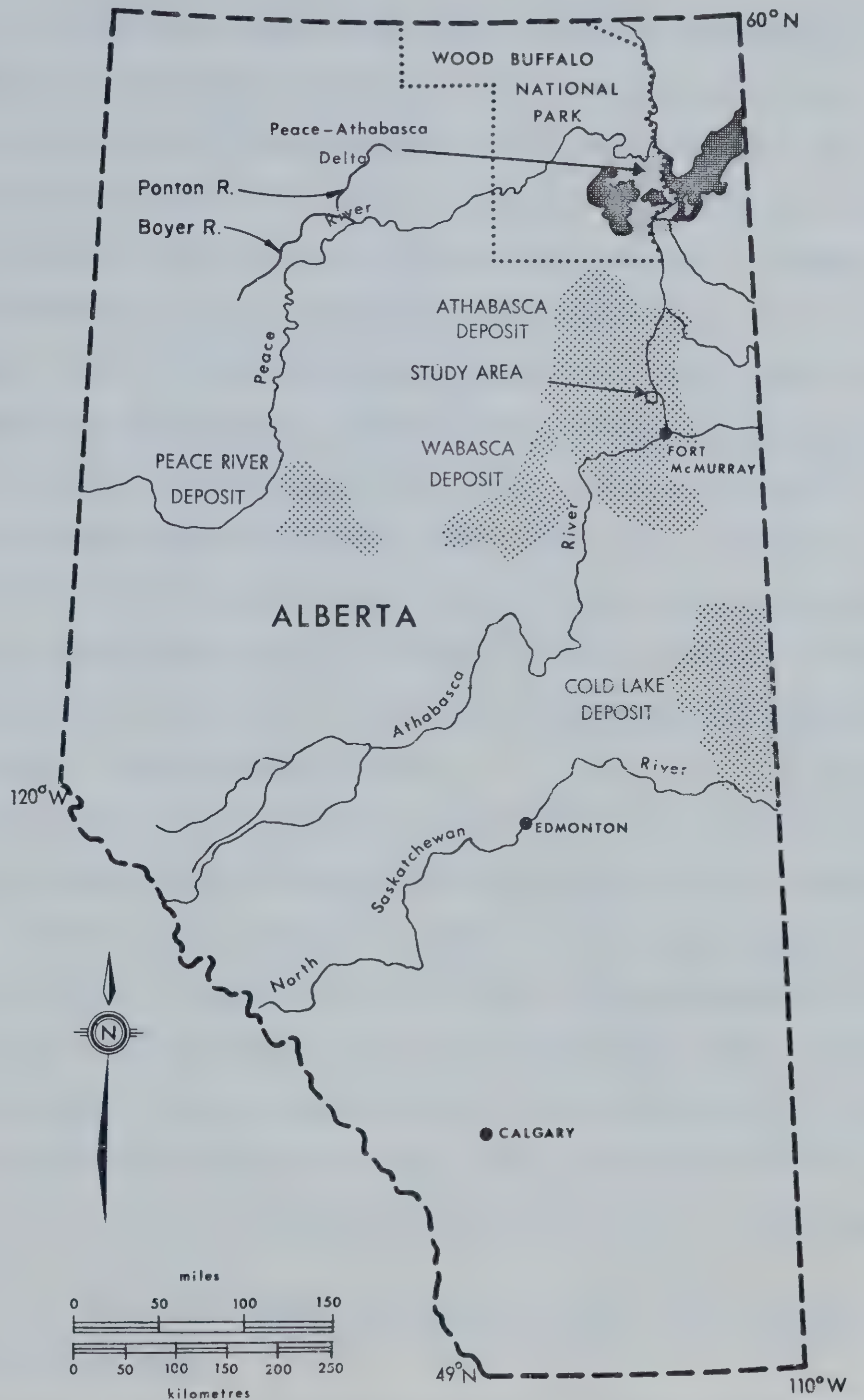
Oil, having become the dominant energy source in North America, cannot be maintained in this position without major exploration and development. In fact Foley (1976) provides a good argument to prove that even with future exploration, the production of North American oil supplies has peaked. Production of conventional crude oil is expected to peak within the next two years in Canada and it appears that production has already peaked in the United States. Even with the addition of the North-Slope oil of Alaska, it is estimated that the United States production will decline slowly. The recent embargo of Mid-Eastern oil exporters has served to emphasize the energy dependence of the United States and Canada upon external sources. A major alternative source of oil in Canada may be the oil sands of north-eastern Alberta.

The first application for construction of a commercial plant to recover synthetic crude oil in the Athabasca Oil Sands was made in March of 1960 (Carrigy and Kramers, 1973). Approval was not issued until September of 1962 because the Alberta Government wanted to protect the limited markets for conventional crude oil production. The regulation was designed to protect the people of Alberta as they are the "owners"

of this natural resource. With increasing demands for oil coupled with decreasing supplies of conventional crude oil, it is now apparent that there will be an unlimited market for synthetic crude oil if it is competitive in price. If the mining is to proceed we must determine whether we can develop mining and reclamation techniques and schemes which provide the smallest degree of disturbance to the site, and in a broader scope to the region. Feasibility of these techniques is important because any mining and reclamation techniques have to be implemented in such a way that costs will remain low enough to be on a competitive level with conventional crude oil procedures.

The Athabasca Oil Sands lie beneath a land surface area of approximately 52,000 square kilometers in north-eastern Alberta (Figure 1.1). An estimated 625 billion barrels of oil in place, is held in the Athabasca Oil Sands (Walwyn and Stodgell, 1973). Importance of Alberta's potential supply in oil sands can be put in perspective when compared to the 10 billion barrels expected to flow from Alaska's North Slope fields. It has been estimated that 10 percent of the Athabasca Oil Sands could be recovered by surface mining techniques (Alberta, 1974). This surface mining would occur in a 2,600 square kilometer lowland area where overburden is less than twice the depth of the mineable formation (Laycock, 1974). Oil which cannot be extracted by surface mining techniques will have to be extracted by in-situ methods, if extraction processes are improved. It should be noted that either method will require large quantities of water for the extraction process using technologies of today.

Figure 1.1 MAJOR OIL SANDS DEPOSITS OF ALBERTA



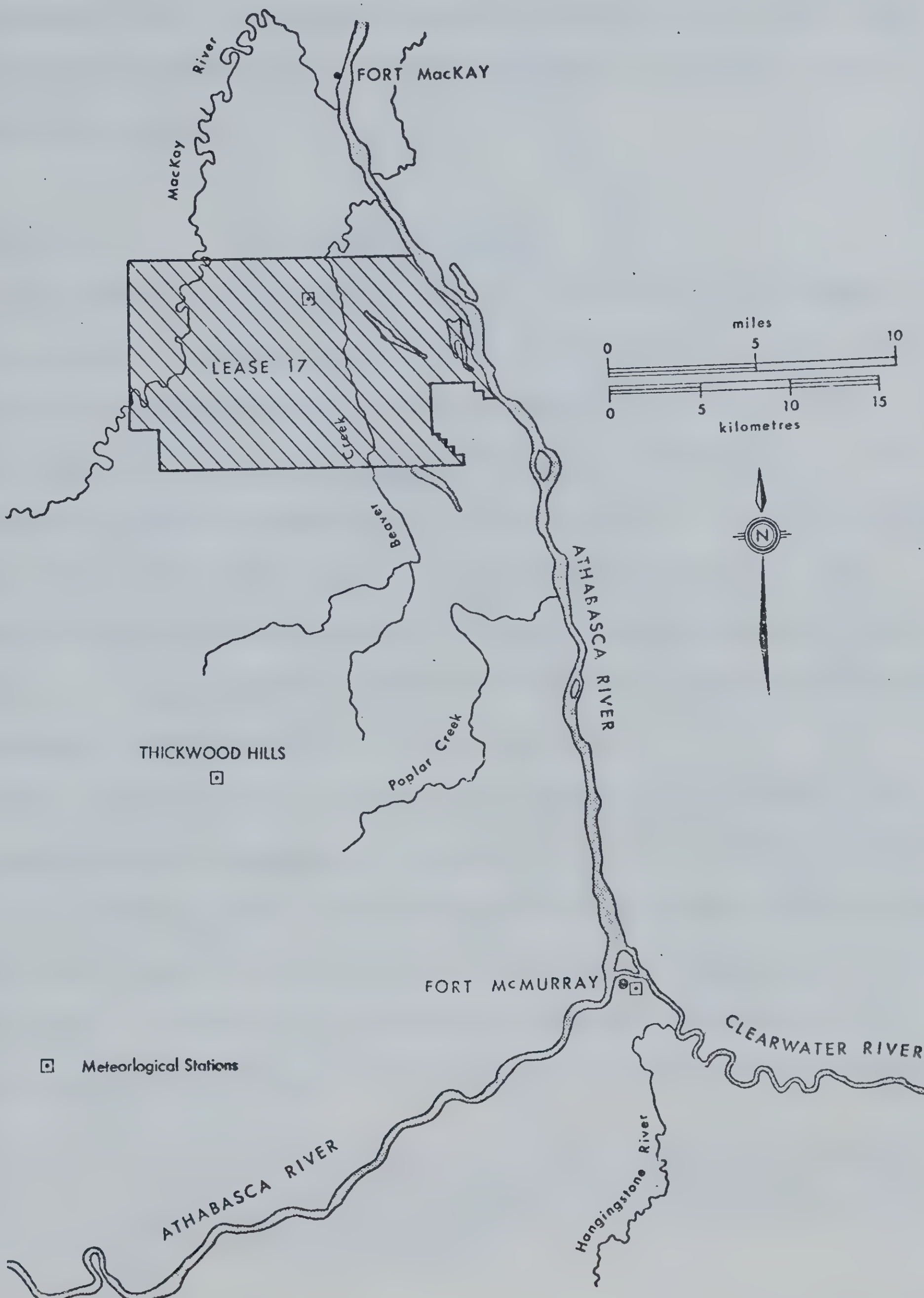
It is outside the scope of the thesis to analyse future demand patterns of world energy consumption trends; it is the author's conviction that unless alternative energy sources are found soon (i.e. nuclear power or solar power) and proved feasible it is imperative that other synthetic crude extraction plants will be constructed. Whether future extraction ventures use surface mining techniques or in-situ processes, both will require vast quantities of high quality water for most phases of the operation. Surface mining techniques require the removal of great areas of forest cover, while in-situ processes also demand that some forest growth be removed. This forest clearing will alter soil moisture storage levels, increase yields, and change regime patterns (some discussion will be included in later sections). A study of water balance patterns will be helpful in gaining an understanding of the physical impact of construction.

The study area is located within this 2,600 square kilometer lowland area approximately 40 highway kilometers north of the Fort McMurray site.[1] The study area includes all land surface drained by Beaver Creek which is situated between 56°47'N and 57°7'N latitude and between 111°33'W and 111°46'W longitude (Figure, 1.1). The Beaver Creek channel passes through Syncrude site in a south to north direction (Figure, 1.2). A dam has been constructed, on Beaver Creek, at the southern end of Crown Lease No. 17 with flow being diverted into the Athabasca River via the Poplar

[1]Within the text of the thesis, study area and Beaver Creek Basin are used synonymously while Crown Lease No. 17 includes only the lower portions of the basin.

Figure 1.2

BEAVER CREEK BASIN AND SURROUNDING AREA



SOURCE: SYNCRUDE, 1975

Creek diversion. Creeks numbered one to four, which originally flowed into Beaver Creek in the area of the plant and mining site,[1] have since been diverted northward into the Athabasca River via the west interception ditch (Figure 1.3).

Section 1.2 Problems and Objectives

The problem, in the broadest sense, is one of identifying water balance patterns in Beaver Creek Basin by examining the component parts of the water balance equation to gain an understanding of each. The actual equation used was developed by Thornthwaite (1948) and is: Precipitation = (Potential Evapotranspiration - Deficit) + Surplus ± Storage Change. The water balance equation itself is simple to compute but measuring the individual variables with reasonable accuracy can be very difficult. In later chapters discussion centers on problems and solutions for accurate measurement of the component parts.

Water balance patterns of Beaver Creek Basin can be divided into two broad classes; internal water balance which includes all land drainage to the tailings ponds and Mildred Lake and the external water balance which would include all surface areas drained by the existing Beaver Creek channel. In ultra conservative estimates Syncrude predicts that 4,755 hectare meters of water will enter the lease site as inflow (Syncrude,

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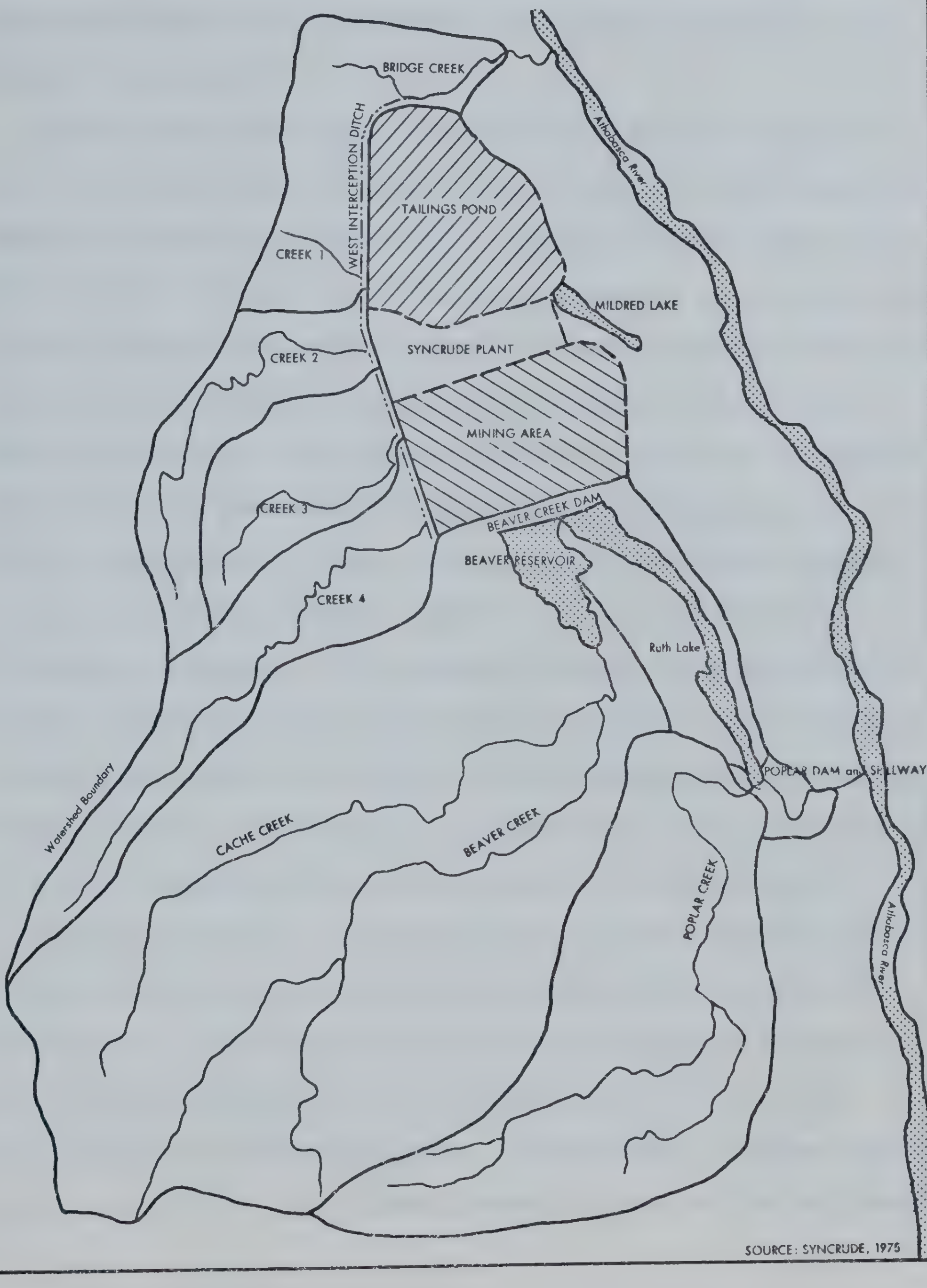
[1]The Syncrude site can be defined as the internal drainage area north of the Beaver Creek dam and east of the west interception ditch. The northern boundary is the north starter dyke and the eastern boundary is the natural divide with Poplar Creek.

Figure 1.3 BEAVER CREEK BASIN



SOURCE: SYNCRUDE, 1975

1971). This is more than one-third as much water as is drawn for domestic and industrial uses by the City of Edmonton (approximately 9900 hectare meters per year). These external water balance patterns will be examined in the thesis.

Internal water balance patterns will be examined on a limited basis. Focus will be placed upon the inflow side of table 6.1; if the study was aimed only at the internal water balance patterns than an indepth review of the literature concerning tailings pond evaporation and study of vapor flux over warm water bodies would also be included. Gross internal water balance patterns are examined as a basis for gaining a better understanding of yield and regime patterns expected in the future drainage of Beaver Creek. The author believes that, although Syncrude personnel seem to think no major water problems exist, internal water balance problems are potentially serious and may hinder future plant operations and environmental management. These potential problems can be eliminated or reduced as many opportunities exist which if implemented would eliminate or reduce water associated problems. These preventative measures include snow pack management, ditching (e.g., complementary to the environment as well as future mining), and drainage along with a number of others.

Although Syncrude (i.e. a joint venture of Imperial Oil Ltd., Cities Service, Gulf Oil, and the governments of Canada, Alberta, and Ontario), has embarked on a three billion dollar construction project only two studies have been conducted which have attempted to define the water balance patterns in Beaver Creek Basin. Laycock (1974) conducted a brief study dealing with the water balance patterns of Syncrude site and Beaver

Creek Basin and then related these patterns to those expected in the Colorado Oil Shale areas. Kellerhals (1973) in a contract for Syncrude conducted a hydraulic study which was heavily meteorologically oriented and even though this information was necessary and useful it did not include discussion of potential future problems. Kellerhals' study filled many of the data gaps in meteorologic data but he failed to speculate on the importance of soil moisture storage levels and vegetation removal.

The initial objective of the author is to present a description of the Beaver Creek Basin, past, present, and future, and relate this description to the water balance patterns expected. This general basin-wide descriptive approach not only provides a good background of the basin characteristics but it is also vital before any site-specific problems can be evaluated. The more site-specific objective of the study, as stated in the contract,[1] was to relate the yield and regime patterns of Beaver Creek and its tributaries to the physical controls involved (climate, topography, soil, vegetation, basin characteristics, etc.) so that a forecast of future flooding, erosion, drainage and supply patterns can be made following the diversions and land use changes of the Syncrude Project. It was necessary to outline a number of more limited objectives in order to fulfill the terms of the contract and also to help in more closely defining the water balance patterns in the Beaver Creek Basin.

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[1]These were the objectives referred to in the contract with Syncrude which provided summer assistance and field expenses.

Below is a listing of the major objectives of the study:

(1) Present background data concerning the physical setting and hydrology of the region.

(2) Compute the monthly and daily water balances using 32 years of climatic data available from Fort McMurray. Compute daily water balance, using meteorological data obtained at Mildred Lake, from July 1, 1973 until the present.

(3) Compare the daily and monthly water balance patterns to determine whether or not a daily water balance provides a more accurate indicator of surplus and deficiency patterns.

(4) Compare values of potential evapotranspiration using the empirical formula developed by Thornthwaite to a semi-empirical formula developed by Penman.

(5) Compare precipitation and temperature data between Mildred Lake and the Thickwood Hills Lookout so that an adjusted water balance can be presented for the upland areas.

(6) Check estimated surpluses, derived from the water balance equation, with the gauged discharges from Beaver Creek and explain the patterns present.

(7) Estimate future yield in Beaver Creek Basin under current land-use practices.

(8) Discuss water management alternatives (some of which need more study) which should be implemented to reduce water yield, and regime problems that might be expected to develop.

(9) Use the water balance calculations to examine the moisture

deficiency patterns which can be used in estimating the need for supplementing water supplies by sprinkling in revegetated and reclaimed areas.

1.3 Justification of Study

Construction of a surface mining operation such as that of Syncrude Canada Ltd. (hereafter referred to as Syncrude) will have significant socio-economic and physical impacts on north-eastern Alberta. Surface mining operations such as Syncrude will alter the hydrology of the plant and mining site and will also alter the hydrology of the surrounding area both directly and indirectly. Land-use changes are evident, even today, and by examining air photos of the area one can see the increasing amount of land which has been cleared of forest cover so that drilling and testing can be undertaken. Construction has resulted in a large influx of people into the area which has resulted in a number of socio-economic problems. This influx of people will advertently or inadvertently modify the water balance patterns of the area. With this influx of people come demands to clear forested areas for homes and industry, construct roads, provide camping and recreation facilities and supply both domestic and industrial water for local developments.

Results of the study may be useful for people working in a number of areas; first, on a regional scale, knowledge of water balance patterns in the Beaver River Basin would be of value to provincial and local planners in future decision making processes. With increasing settlement of the area will come increasing demands upon the water resources of the area including recreational, industrial and domestic. It appears that

sufficient water is available to meet future demand but timing of flow and location of users may cause competitive uses to develop (i.e. recreation such as canoeing for fishing in a stream used to dilute pollution by industry). Definition of water balance patterns in Beaver Creek Basin will serve as groundwork study with results being transposed to study similar basins in the area. Many characteristics and patterns evident in Beaver Creek Basin will certainly exhibit the same features found in surrounding basins. These yield and regime patterns can be analysed for similar basins without further extensive studies. One of the foremost topics discussed in the media today is the water related problems ranging from the drought in western North America to over use and pollution occurring in the humid areas of eastern North America. Wherever there is a hamlet, town or city there is usually some water related problem. Presently, water is an abundant resource in north-eastern Alberta and demands and uses of the water have provided only minor changes in water balance patterns. One can be assured that with future development and settlement water associated problems will occur. Hence, a study providing base line data on water balance patterns of Beaver Creek Basin can only help planners and decision makers in limiting the extent and degree of these water resource problems.

Basic knowledge of the water balance patterns (derived from this and other studies) in the Beaver Creek Basin will be of specific value to Syncrude planners as mining and reclamation continues. A better understanding of the water balance patterns will allow Syncrude planners to assemble concise site development plan revisions which are required

annually by the Province of Alberta. Environmental impact statements such as those written by Syncrude personnel in 1971 and 1973 dealt with water, usually when a problem had been discovered or foreseen for the future. Water associated problems were referred to and mentioned throughout the environmental impact statements but only when these water problems presented a hazard or nuisance to some phase of the mining or plant operations. A solution would also be presented and most often this involved an engineering structure. A good example is seen in the ever increasing size of the tailings ponds put forth as a solution to the conservative estimates of increases in surpluses of local origin. These water balance patterns and associated water problems vary both spacially and temporally; these two factors have been given little, if any, consideration in the environmental impact statements presented thus far. Once the changing water balance patterns are recognized by government officials and environmental groups, more emphasis on water associated problems will be required. Environmental impact statements are the tools which provincial reviewers must use in granting permits which allow a company to extract a non-renewable resource and these reports should be as accurate, informative, and understandable as possible.

Finally, results presented in the thesis are hypothetical and will only occur under a given set of conditions. Problems expected (i.e. greater yield and flashier flow) can only be envisaged through knowledge of expected land-use changes. Any future change in land-use as well as in extraction technology will alter the findings of the author. Estimating surplus under above average precipitation and soil moisture storage conditions should provide an idea of the most acute surplus problems

that will occur. These estimates may be used by Syncrude, government, or contractors for any number of purposes. Good planning through prior knowledge of water balance patterns can prevent harmful environmental changes in the Beaver Creek Basin. Land-use changes which are planned will be important factors in defining future yield and regime patterns. Many people would argue that there are too many variables which can alter the water balance patterns of an area; the author believes that a good estimation of the overall water balance patterns can be achieved by a thorough study. If we have no idea of the general water balance patterns it is nebulous to study more specific water balance problems. Thus it is difficult to place local problems in perspective and design of control structures may range from wholly inadequate and costly because of later construction to greatly excessive and again costly (e.g. The Poplar Creek Control structure may prove to be a possible overdevelopment in control structures).

1.4 Method of Study

In conducting the study it was necessary to review and incorporate a number of methods which help to define the overall water balance patterns. When studying the movements, actions, and effects of a substance as ubiquitious as water a combination of methodologies was needed in defining the water balance patterns. Personal communication with people working in the study area was one way to gain an insight into what was happening, especially when these people are working in the study area from forty to fifty hours per week. During the field season (May 1976 to

March 1977) Syncrude employees were helpful in pointing out observed rainfall-runoff relationships. Discussion also centered on the type of storm activity and patterns noted during the summer of 1976. One Syncrude employee had made visual observations on the west interception ditch and made note of the reaction time in Beaver Creek Basin. Many other discussions focussed on the general water balance patterns in the study area with many phone conversations relating to snowfall and snowmelt occurring during the winter of 1976-77. Other interviews with AOSERP (Alberta Oilsands Environmental Research Project) personnel were helpful in providing an impression of relevant studies which are currently in all stages of completion and it was also necessary to find out if future research would be complementary to this study. (As a general rule AOSERP'S goal is to monitor all changes in quality which take place in systems and they devote little time to determining quantity changes).

After conducting interviews with many people working in different capacities in the Oil Sands a relevant literature search was used as an aid in defining water balance patterns and potential problems of the Beaver Creek Basin. A water balance concept based on empirical procedures was developed by C.W. Thornthwaite (1948, 1955, 1957) using a bookkeeping procedure keeping a record of all incoming and outgoing water. This concept is central to this thesis as are the adjustments made for northern latitudes suggested by A.H. Laycock (1960, 1967, 1973, and personal communication). Reasonable results have been obtained using this same basic concept by Laycock (1957, 1967, 1973), Erxleben (1972), Wight (1973), MacIver (1970), Kakela (1969), and Hallock (1976). Strong

points and shortcomings of this methodology will be discussed in section 4.3.

The literature search was used as a means of determining areas where errors tend to occur in gauging and estimating precipitation, soil moisture storage levels, and potential evapotranspiration. Bruce and Clark (1966) present an excellent review of literature concerning accurate gauging of precipitation. There has been much research conducted to develop formulas which can be used to predict the amount of moisture in the soil capable of being transpired by the vegetative cover and also the amount of water capable of being evaporated from a water surface. Thornthwaite combined the terms to form the term evapotranspiration which is used throughout the thesis. This estimation of potential evapotranspiration is one component of the water balance which can only be gauged accurately under ideal field conditions while in most studies estimates must be used. Many researchers have attempted to estimate potential evapotranspiration in various studies. A review of Thornthwaite (1948, 1955, 1957), Penman (1948, 1956, 1963), Blaney and Criddle (1950) and Budyko (1956, 1974) is included in the thesis. A comparison of potential evapotranspiration estimates using two of the most popular methods, Thornthwaite and Penman, was done as a check to see if Penman's method could be used to accurately estimate potential evapotranspiration in northern Alberta. All of the methods previously mentioned require a more sophisticated level of climatological data than is available from Mildred Lake (the meteorological station in the study area). The author believes that none of the other methods would provide more accurate

estimates than Thornthwaite's; the other methods have been used in many areas but so many of the values must be interpolated or estimated that much of the point of using them is lost. Finally, the resources and time required to obtain and process the data using any of the other methods is beyond the scope of the thesis.

Air photo interpretation was used to determine vegetation type, location and density. Air photos taken in the 1960's were used to determine vegetation type and density in the areas cleared for mining and extraction processes in the early 1970's. Finally, air photos were used along with reports on the surficial geology of Waterways and Bitumont (Bayrock and Reimchen, 1973) and surficial materials mapping by the Resources Capability Group, Resource Evaluation and Planning Division of the Department of Energy and Natural Resources to estimate soil moisture storage capacities to be used in water balance calculations.

Methodologies mentioned above will be combined to better explain water balance patterns in the Beaver Creek Basin. There are many different studies which were invaluable in explaining different problems which arose during the course of the study and these are mentioned in different sections. All of the methods and studies mentioned in this section and more were brought together, reviewed, and used to build as accurate a regional water balance description as possible. This water balance can be thought of as a tool used to meet the main objective to provide useful information relating to the environment for water management purposes.

CHAPTER II

Physical Setting

2.1 Introduction

Any alteration of the drainage pattern of a stream will affect the physical characteristics in the basin either directly or indirectly. These effects are not always adverse in nature. Mustonen (1976) at the Leningrad Symposium of the I.H.P. reported that 4.5 million hectares of peatland had been drained for forestry purposes by 1975 in Finland with 7.5 million hectares scheduled to be drained by 1985. This is nearly 25 percent of the land area of Finland. The drained land is also considered to be more productive in terms of wildlife and recreational uses and water yields are substantially increased. The opportunity for similar changes in Alberta is present if we are to significantly increase potential for forest production in the future. Present patterns are neither optimal nor the most desirable in terms of restoration.

This chapter includes a review of the physical parameters which will be altered by the damming and diversion of Beaver Creek and the clearing and construction in Beaver Creek Basin. Focus is placed on discussion of how these physical parameters affect or are affected by water resource use and patterns in the study area. Discussion of the physical characteristics as they relate to water resources on a regional basis will provide a framework for understanding patterns and future problems associated with development of land areas relating to timing, regime and yield patterns in the study area.

2.2 Physiography

Beaver Creek is a tributary of the Athabasca-Clearwater River System which drains all of the Oil Sands area.[1] The Athabasca-Clearwater River system has incised 200-300 feet into the interior plain. Most of the tributaries of the Athabasca River flow out of the surrounding highland areas. Muskeg Mountain rises to the east of the Athabasca River to an elevation of 633 meters above sea level (ASL), Stoney Mountain south of Fort McMurray rises to 833 meters ASL, Birch Mountain rises to the northeast of the study area to an elevation of 900 meters ASL, and the Thickwood Hills west of Fort McMurray rise to an elevation of over 566 meters ASL. The Beaver Creek and tributaries drains the northern flanks of the Thickwood Hills and the lowland area north of the Thickwood Hills between the MacKay and Athabasca Rivers (Figure 1.2).

Beaver Creek flows through and drains portions of three physiographic regions. Headwaters of Beaver Creek are located in the upland area called the Thickwood Hills. This upland area reaches an elevation of just over 510 meters ASL which is approximately 210 meters above the lower reaches of the basin. Regional slope in the Thickwood Hills is in a northerly direction with a very gradual slope existing over most of the Beaver Creek Basin. After dropping out of the Thickwood Hills

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[1]The Oil Sands deposit referred to is that termed Athabasca and actually the Wabasca, Cold Lake, and Peace River deposits are in different drainage basins; (see figure 1.1).

Beaver Creek flows over a broad flat to gently rolling plain. Current construction and clearing is taking place in this lowland area of Beaver Creek Basin. Within this area are many hectares of marsh and muskeg which make up much of the poorly drained portion of the basin. There are many small ponds throughout the basin that are visible on air photographs of the area (Airphotos, 1972, 1974). Large Beaver populations have created a number of beaver dams which provide artificial storage on Beaver Creek (Syncrude, 1976 Uncontrolled Mosaic). After flowing out of the highland areas and across the relatively flat lowland areas Beaver Creek flows north and then bends east crossing under Provincial Highway 63 before cutting into the escarpment along the Athabasca River. A drop of approximately 280 meters occurs in a distance of 42 kilometers.

These three physiographic regions are significant because each requires individual consideration when explanation of potential patterns of yield, regime and erosion are discussed. Upland areas with increased precipitation and decreased potential evapotranspiration provided the greatest yield per unit area before land-use changes occurred. The broad flat lower level table land is the area of major land-use change with subsequent changes in yield and regime patterns. These two areas will require much more study and discussion than the escarpment area because these two areas comprise the greater part of the total basin area. The small area of the escarpment probably receives less precipitation, because of its valley location but the northeasterly aspect and good drainage enable it to have the best forest growth in the study area.

2.3 Climate

A climatic classification scheme developed by Köppen and revised by Geiger and others places Beaver Creek Basin in a Dfc or subarctic type climate (Trewartha, 1968). According to this classification scheme the study area is located in a cold snow-forest type climate with the average temperature of the coldest month below -3° centigrade and the average temperature of the warmest month above 10° centigrade but fewer than four months above 10° centigrade. Exceptions have occurred such as 1976 when mean monthly temperature was greater than 10° centigrade for five months of the year. Thus, the climate of the study area would have been classified classified Dfb in 1976 and the northern margin of Dfb climates includes the study area in warmer years. Using this classification there are no pronounced dry seasons throughout the year. A review of water balance patterns, especially in the dryer years, shows that large deficits (i.e. drought) can occur in all soil moisture storage levels. This type of classification also refers to the summer season as short and cool. This is the case in many years but in the summer of 1976 temperatures of 23° centigrade were not uncommon and a temperature as warm as 30.2° centigrade was recorded. In some years the climate of the study area is not far from being classified a Bsk or Steppe type climate, especially when warm temperatures and low precipitation are recorded causing high potential evapotranspiration rates.

There are too many faults inherent in the above classification as well as in other similar global classification schemes for it to meet our needs but useful perspectives are provided: first, the great

continentality of the study area means that there are great fluctuations in temperature and precipitation from day to day and year to year with an average only being a composite of these fluctuations; second, the fact that there is no pronounced dry season is more a function of cool temperatures than of great amounts of precipitation. Actually the climate of Beaver Creek Basin is not just a listing of average temperature and precipitation but as has been stated it is "the long-term manifestation of weather in all forms" (Longley, p.1, 1972). Averages and means are best used to define the climate of Beaver Creek Basin, as they are one indicator of climate as a dynamic entity.

The study area has a relatively short frost-free season of approximately 60 days but wide fluctuations from year to year can greatly increase the length of the frost-free season to nearly four months or reduce it to less than 30 days. It is possible for a 0° centigrade reading to be recorded in any month of the year. Mean annual temperature in Fort McMurray is -0.5° centigrade with fluctuations from 1.7° centigrade to -2.8° centigrade. Mean annual precipitation for Fort McMurray is 44 centimeters while potential evapotranspiration has averaged 49.2 centimeters per year. Therefore, a deficit occurs in most years by mid-summer, especially since part of the precipitation runs off in spring.

Summers in the study area are short with warm daytime highs and cool overnight lows, with a mean daily maximum of 24° centigrade and mean daily minimum of 8.3° centigrade for July. On the average there will be 15 days during the year when the temperature will rise to 26.6° centigrade (80° Farenheit) and it is not uncommon for a temperature of 33°

centigrade to be recorded (Longley, 1972). Although temperature is a good indicator of the intensity of the incoming solar radiation the long hours of daylight in mid-summer add to the amount of potential evapotranspiration that would normally be expected. In the spring months of late March, April and May energy from solar insolation is needed to melt ice and snow and thaw out frozen ground, thus the heat available for potential evapotranspiration is reduced (Wight, 1973).

Precipitation during the summer months of June, July and August averages between 20.3 and 22.8 centimeters. Precipitation over Beaver Creek Basin is usually of low intensity with a one day maximum precipitation in a 10 year return period of between 5 and 6.4 centimeters (Longley, 1972). A change in storm type occurs during the summer period; in spring and early summer, the storms are cyclonic in nature with stratus type clouds producing a general low intensity rainfall over a large area but by mid-summer the main cyclonic track is north of the study area and precipitation is largely convectional in origin. It is the late spring and early summer rains which usually produce the maximum yearly recorded flow (as in 1972). In most cases snowmelt recharges the soil moisture supply and produces some runoff but in may years high yields can be noted from relatively light rains which fell before significant soil moisture depletion has taken place (Figure 3.3).

Autumn is often thought of as being the months of September, October and November but in the study area autumn-like weather may occur in late August with winter setting in by mid-November. Precipitation drops off markedly in autumn with average precipitation being 5.3 and 2.4 centimeters

in September and October, respectively (Environment Canada, 1945-76). Most of this precipitation in late summer and early fall goes into soil moisture recharge to replace the large draw down of soil moisture which takes place in most summers.

Winters in Beaver Creek Basin are characterized as being cold and dry with the light precipitation which does fall being largely in the form of snow. Very little snowmelt takes place during the winter because northerly locations such as the study area are usually dominated by Continental Arctic air. Most of the snow which falls during the winter months is held in surface detention storage for later release in the spring. Median snow depth in Beaver Creek Basin on February 28 is from 40 to 45 centimeters; here again there are large variations from year to year (Longley, 1972). The amount of moisture in the snowpack is more important, for water balance computations, than the actual depth of the snow but in Canada a ratio of 10:1 is usually used to convert snow to water equivalent (at Fort McMurray a nipher gauge is used now).

Prevailing wind direction in the winter changes from east-northeast in December to west-northwest by mid-January. A northerly component dominates the wind direction during the winter and this pattern is important when looking at the drifting patterns. The wind speed is also important in determining drifting patterns; a loose friable snow will be transported in the air at wind speeds as low as 3 to 5 meters per second. Maximum wind speed in December, January and February were over 15 meters per second and almost always were from the north-northwest. Thus, drifting of snow can be expected in Beaver Creek Basin, especially in cleared

areas.

Spring, normally considered to be the months of March, April and May is a short season in northern Alberta, as a change from cold temperatures and snow cover to warm almost summer-like weather takes place in a matter of weeks, with a major variation in time of occurrence between years (e.g. runoff in 1974 and 1975 began in mid-April while in 1976 it began in mid-March). The length of the snowmelt period is greatly influenced by the timing and duration of milder temperatures associated with spring. The spring snowmelt provides for quick release of moisture held throughout the winter. Conditions during the melt season determine the amount of water which goes into soil moisture recharge and that which runs off as surplus. An extended melt period with a large number of freeze-thaw days allows for maximum infiltration. If precipitation was adequate the previous fall, and a hard freeze occurred before major snowfall, a rapid thaw of the snowpack may largely runoff because of the low infiltration capacity of frozen soil. The 1956 United States Army Corp of Engineers handbook on Snow Hydrology contains a complete discussion on snowmelt characteristics (U.S. Army, 1956).

2.4 Bedrock Geology

The Athabasca Oil Sands have been defined by Carrigy and Zamoa to include the oil-impregnated portions of the Lower Cretaceous strata found in north-eastern Alberta in the lower Athabasca River area (Carrigy and Kramers, 1973). The Oil Sands deposit extends from 55°N to 58°N latitude between the fourth and fifth meridians (Figure 1.1). Absolute boundaries

of the oil sands deposit have not yet been determined. The deposit is pinched out by a ridge of Devonian limestone in the west while the northern boundary has not been closely determined because very little drilling occurs in Wood Buffalo National Park. The Oil Sand deposit pinches out against the Canadian Shield in the northeast while eastern and southern limits are a matter of definition as a gradual thinning of oil impregnated sands takes place in these directions.

Irregular pre-Cretaceous topography played a major role in controlling the thickness and areal extent of the overlying McMurray formation. The McMurray formation is the earliest formation which lies unconformably on the Devonian surface. Sands and silts impregnated with viscous oil, which comprise the McMurray formation, tend to fill in the valleys and depressions of the older Devonian surface. This produces a marked thinning of the McMurray formation over the highland regions of the old Devonian landscape. The McMurray Formation developed during the time in geologic history (i.e. 275 to 250 million years ago) when much of the north-eastern Alberta was inundated by water. This water body varied from a shallow lagoon to an open sea. A large river entered the southern portion of this sea and there was a great build up of deltaic material. By the early stages of the Clearwater Marine advance the hills and ridges of the Devonian limestone had been reduced to shoals and the wave action of the sea provided the energy to clean sorted glauconite sands. These sands filled in the remaining depressions of the old Devonian landscape and are now reservoirs for some of the heavy crude oil.

The McMurray formation averages approximately 53 meters in thickness

with the Clearwater formation being 76 to 91 meters thick and overlying the McMurray formation. Grand Rapids sandstones 85 meters thick overly the Clearwater formation. La Biche marine shales comprise the rest of the Cretaceous deposits which can be up to 600 meters in depth. Carrigy (1959) provides an excellent map showing the variations in different deposits.

There are three major geologic sequences which formed the surface of the pre-Cretaceous landscape. Between the Devonian and early Cretaceous era there was a period when deposition was halted. Subareal erosion and weathering altered the surface of the Devonian landscape. Calcareous shales were weathered and eroded to produce a landscape which consisted of wide broad river valleys meandering through low rounded hills. It is surmised that block faulting in the Precambrian rock has caused the formation of ridges over which the McMurray formation thins out, (Carrigy, 1963). Drilling has proven that the McMurray formation thins markedly but there has been no absolute proof of Precambrian faulting. Leaching of Elk Point evaporites within the Devonian landscape created many large depressions for deposition of sands and silts of the McMurray formation. These three geological sequences played the major role in shaping the final landscape of the Devonian surface.

Some water management problems are expected from flow systems within the bedrock geology. Members of the Oil Sands Environmental Study Group (1974, p.14) co-ordinated by H.A. Gorrell stated: "we believe that the groundwater flow systems in the McMurray area offer a number of severe potential hazards to mining operations and the environment." The Methy

Formation, formed as a reef in Devonian times locally has high porosities and permeabilities and the hydrostatic head reaches almost to the surface. If depressurization of the McMurray formation occurs there is a chance saline waters from the Methy formation may have vertical access through areas that were removed by solution in the lower Prairie Evaporite formations. The Cretaceous Clearwater and Grand Rapids formations are not thought to contain major aquifers and water that is present in these formations is usually fresh.

Aquifers occur at and near the base of Pleistocene bed as meltwater channels were cut into the underlying bedrock surface; these were then filled with materials of high porosity and permeability. Local flow systems will also provide additional water to the mine pit. No estimates of flow or extent of recharge areas have been conducted. Thus, discharge from deep bedrock formations with their saline waters as well as discharge from local flow systems will provide future disposal problems (see section 6.2 and table 6.1 for further discussion). Many of these disposal problems can be kept in check with only minor water management alternatives.

2.5 Soils

Climatic and vegetative cover differences have resulted in the development of two distinct soil types in Alberta. Chernozemic soils have developed under the dry grassland vegetation in southern Alberta while Gray Wooded soils have developed in the cooler more moist areas of northern Alberta. Preliminary soil mapping has shown that Beaver

Creek Basin contains predominantly soils of the Gray Wooded group which have a clay loam texture (Lindsay 1958, 1963). These soils can be associated with the parent material from which they were formed.

Although the Gray Wooded Soil group is predominant great variations exist within the study area. Gleysolic soils have formed from till and lacustrine parent material in the poorly drained areas while Gray Wooded soils with a high clay content were formed from the same parent material but on well drained sites. Local areas of Podzols have developed on the well drained sandy glaciofluvial material. The areal extent of these sandy deposits has not been determined but they occur most frequently in the lower reaches of Beaver Creek Basin (Lindsay, Pawluk and Odynsky, 1963). Isolated areas of podzols were noted during the field season on former beach ridges in the Thickwood Hills. Organic deposits have developed on some of the poorest drained sites.

All of these soils have a very limited potential for agricultural development. Gray Wooded soils in the study area consist of an Ae horizon which is gray in color and very low in organic matter. The Ah horizon, comprised of humus and mineral matter, is almost always less than 5 centimeters in depth and offers very little protection against erosion. At best these Gray Wooded soils could be used for pasture or forage crops.

The different soils in the study area play a role in water balance patterns. In one of the earlier works Colman (1948) showed the different water holding capacities of the soil (Table 2.1). Very little difference exists in the amount of water available at pore saturation but the large grained soils (i.e. sand to loam) can hold much less water at

Table 2.1: Water Holding Capacity of the Soil

(inches of water per foot of soil)*

Soil Type	Pore Saturation	Field Capacity	Wilting Point
Sand	5.0	0.9	0.4
Sandy Loam	5.0	1.8	0.7
Loam	5.0	2.7	1.1
Clay Loam	5.4	3.4	1.7
Clay	5.4	5.0	2.5

* The table was left in English units of measurements to show the effect of the original work.

field capacity. The difference between pore saturation and field capacity is referred to as detention storage; this is the amount of water held in the soil subject to the pull of gravity. Thus, the clay loam soils in the study area provide more storage at field capacity than the sandy soils. The retention storage (i.e. field capacity minus the wilting point) is the water held against gravity which is readily available for plant growth. Thus, more water is available for plant growth from the finer textured soils but these finer textured soils (i.e. 25 centimeter and 15 centimeter storage capacities) also hold a greater percentage of water in storage after the wilting point is reached.

The infiltration rates of the different soils will also alter runoff. Soils with large particle size have greater infiltration capacities

while the clays and clay loams have much slower infiltration capacities. Clearing of this clay loam could lead to increase in runoff as the raindrop action causes silt and clay particles to float across the surface and cause surface sealing (Holtan,1964). Thus, clearing large tracts of land in the Oil Sands area will not subtract from prime agricultural land (this has happened with extraction of many natural resources), but this is not to say that problems of erosion and increase in yields will not develop.

2.6 Flora

The Beaver Creek Basin is located within the boreal mixedwood forest zone of Alberta (Moss, 1955). This mixedwood forest is mainly comprised of deciduous poplar (Populus tremuloides) and white spruce (Picea glauca) stands. Also located within the mixedwood zone are muskeg areas associated with black spruce (Picea mariana) and willow (Salix). These muskeg areas have characteristically poor drainage and are capable of holding vast quantities of water in detention storage. Much of this muskeg is interspersed with black spruce on the wet flatlands west of the construction site. MacFarlane (1958) uses the Radforth Classification System to point out the difficulties in delimiting much of this muskeg.

Jack pine (Pinus banksiana) are located on the driest sites in the basin. Jack pine are almost always associated with Podzol soils formed on the well drained sandy outwash material in the lower reaches of the basin along the margins of the Athabasca River. During the summer field season the author found stands of Jack Pine growing on the well drained

former beach ridges in the Thickwood Hills. There is a great diversification of understory vegetation associated with the different stands and for an excellent discussion and listing of these species the reader should see Moss (1955). Species are discussed in later chapters where they are found to play a unique role in the water balance.

The following is a listing of eight community types which have been associated with the study area (Syncrude p. 6, 1973):

1) Jackpine (Pinus banksiana),
2) Jackpine-Aspen (Pinus banksiana - Populus tremuloides),
3) Aspen (Populus tremuloides),
4) White Spruce - Aspen (Picea glauca - Populus tremuloides),
5) White Spruce (Picea glauca),
6) Rivervine (Populus balsamifera - Picea glauca),
7) Black Spruce (Picea mariana),
8) Sedge (Carix) (Syncrude p.6, 1973).

This listing of community types can be used as an indicator of soil type which in turn can be used to delimit soil moisture storage levels in the area. Vegetation type as well as maturity and vigor of the stand plays an important role in the amount of water transpired which indirectly influences the runoff from the basin.

Stands of jackpine are found on the drier sand ridges which are stabilized sand dunes developed in a more arid climate in earlier times. Jackpine are the only species which flourish on these sand ridges. These ridges have high infiltration rates and very good drainage. Jackpine-Aspen communities may develop on sandy outwash soil with a high

water table. A major part of Beaver Creek Basin is vegetated by a successional series from aspen to aspen-white spruce to white spruce (Le Roi, 1973). This successional series provides a mixedwood mosaic forest directly related to the fire history of the area. Aspen is one of the first species to revegetate a burned over area as the new saplings grow from root suckers from surviving root systems. White spruce invade the aspen forest years after a fire because regeneration of them is dependent on a source of seeds. White spruce is the climax vegetation but disease and fire prevent all but localized stands of pure white spruce. Thus, this series is dependent on soil moisture as well as the history of fires in the area. This series grows on all soil types in the study area except the dry sand ridges and organic soils of muskeg.

Very little of the timber in the Beaver Creek Basin is harvestable because of the poor drainage and history of fires in the area. Climax vegetation has rarely been reached in north-eastern Alberta because of the high frequency of fires. Records for 1957 show that in the previous 15 year period over 20 percent of the boreal forest area had been burned (Le Roi, 1973). This is a short time span considering the 100 to 200 year life span of the white spruce. Fires can greatly increase the water yield of a basin as well as alter the regime. Water balance patterns have been altered from time to time when parts of the study area have been burned. Fire frequency can be closely associated to drought and there is potential in using the running bookkeeping procedures of the water balance as an index of the frequencies, intensities, durations and extent of droughts.

Pure aspen stands are uncommon in the study area because white spruce will spread into the area as seed becomes available. Pure white spruce stands are also rare, as they are the climax vegetation and fire has prevented this from occurring except in very small protected stands. A white spruce-aspen community dominates the study area and stands vary in percentage and maturity according to the fire history.

Muskeg is very common throughout the study area. Stands of black spruce are dense in areas with a relatively thin layer of peat. With increasing thickness of peat and increasing acidity the black spruce give way to semi-aspen areas with scattered clumps of birch (Betula spp) and willows. These muskeg areas play an important role in altering evapotranspiration and runoff characteristics in the study area. These organic layers can store large quantities of water in dead storage and provide very slow release of this water in dry periods. Drying at the surface can decrease surface water contents to almost zero but a few centimeters below the surface the organic deposit may be at nearly 100 percent of soil moisture storage capacity. Thus, the surface layer provides an insulating mat between the air and water held in storage.

Syncrude clearing and mining operations have removed forest cover of very low productivity. There is a possibility that fires will be brought under control more rapidly to protect the heavy investment in the area. If drainage was improved the forest cover could be made more productive than it is presently and evapotranspiration rates could be increased.

2.7 Fauna

The poor drainage, large areas of muskeg and black spruce, combined with the severe winters typical of Beaver Creek Basin as well as north-eastern Alberta has provided a habitat of relatively low carrying capacity of bird, animal and fish life.

Clearing coupled with the construction of the Beaver Creek Dam near the southern boundary of Crown Lease No. 17 has had a direct effect on the marginal fish population. Studies conducted by Syncrude have found very few game fish in Beaver Creek. Arctic Grayling use the gravel bottom of the lower reaches of Beaver Creek as a spawning area. After spring break up the Arctic Grayling leave the sediment laden waters of the Athabasca River and spawn in the headwaters of Beaver Creek (Syncrude, 1973). With construction there has been an increase in suspended sediment load and a change in flow patterns but the final changes in spawning patterns have not been determined. White sucker which are rough fish were also netted in the study. Small numbers of many other species were netted during the study. Construction of the reservoir below the construction site may provide an alternative body of water capable of supporting fish. Disposal of saline waters from mine depressurization may be a problem hindering fish life.

Waterfowl in the study area will be directly affected by altering of water courses and creation of artificial reservoirs. Only intensive study will provide knowledge of the final effects of the altered water courses. Renewable Resources Consultants Ltd. conducted a study of the migratory waterfowl in the fall of 1973 and sighted over twenty species

of ducks. Mallards (Anas platrhynchas) were the most common species observed with Widgeon (Mareca americana) and Coot (Fulica americana) being the next most common. A good description of the types of species spotted as well as timing of migration is given in the report conducted by the Renewable Resources group (Syncrude, 1973).

Species identification of migratory waterfowl is not the focal point of this section but more importantly changes in migration patterns caused by physical alteration of water bodies and streams should be outlined. Currently, Ruth Lake and Mildred Lake offer good stop over habitat for "diving" ducks such as coot and Goldeneye (Bucephala clangula) while Beaver Creek, the Mackay River, and sloughs in the study area offer stop over habitat for "dabbling" ducks such as mallards. Favorable stop over sites on Beaver Creek are most commonly associated with the beaver dams (Syncrude, 1973). The Peace-Athabasca River delta is located approximately 160 kilometers north of Beaver Creek Basin and is a very large staging area for migratory waterfowl. After leaving the Athabasca staging area most waterfowl pass over the study area in search of grain producing regions in central or southern Alberta or else they fly southeast from the delta into Saskatchewan (Syncrude, 1973). Studies have been conducted which show that major changes in a water course can affect migration patterns of migratory waterfowl. There is concern that Beaver Creek Reservoir and the warm water of the tailings ponds may attract waterfowl to the area. There may be a need to make these water bodies unattractive for waterfowl to discourage their use of them. At the same time environmental enhancement of Horseshoe Lake could be provided to attract the majority of waterfowl which stop over during migration.

Ungulates are common although not abundant throughout Beaver Creek Basin; moose (Alces alecs) are the most numerous species in the area with mule deer (Odocoileus hemionus) and woodland caribou (Ranger caribou) also present. These large ungulates are not expected to be adversely affected by the Syncrude operation. Human intrusion presents more of a problem for many types of animal life than the clearing of a minute percentage of the boreal forest. Beaver Creek Basin has a very low carrying capacity for ungulates as well as other animal life because of the poor vegetation and the severe climate. Thus, Syncrude should not significantly affect the animal population of the region. Further discussion of wildlife indigenous to the area can be found in Alberta A Natural History (Hardy, 1967).

2.8 Human Settlement

Original settlement of the Oil Sands region was dependent on water as a means of transportation; future development like past development will be largely dependent upon the water resources available. Peter Pond, a fur trader with the North-West Company, was the first European to see the outcrops of oil sand along the banks of the Athabasca River in 1778. Pond's only use of the oil sand was as a sealant for the seams of birch bark canoes. Pond's elusive dream was to discover the North-West Passage but he ended up joining the North-West Company which traded with the Chipewyan Indians of northern Alberta in return for prime furs. For nearly 100 years a village at the confluence of the Athabasca and Clearwater Rivers served as a trading post for the Indians and trappers of

northern Alberta (Chalmers, 1974).

H.J. Moberly came to the junction of the Athabasca and Clearwater Rivers in 1870 with the intention of developing Fort McMurray into a transportation terminus; there were plans for a steamboat route extending down the Athabasca and Slave Rivers for nearly 480 kilometers. In the early 1870's, before the first steamboat arrived, Moberly was responsible for providing improved land transportation around Methy Portage which is located between the Clearwater and Churchill river basins east of Fort McMurray. Thirteen years elapsed between Moberly's founding of present day Fort McMurray and the arrival of the first steamboat in 1883. This led to the development of Fort McMurray at the head of the water highway to the Arctic and also the fever of a boom era (Chalmers, 1974).

For almost two hundred years the inhabitants of north-eastern Alberta had an economy based on trapping, trading, and transportation but they were always hoping for the boom. Over 100 years ago John Macoun, a Canadian botanist, gave an accurate account of what was finally happening:

> "on account of the rain, our camp was formed in the woods, and was both wild and picturesque. Three rousing fires were built (one for each boat) and around these in the darkness flitted dusky figures, some cooking, and all talking or laughing, without thought of rain or any other matter than present enjoyment. Long after the noises ceased I lay and thought of the not far-distant future, where other sounds than these would wake up the silent forest; when the white man would be busy, with his ready instrument, steam, raising the untold wealth which lies buried beneath the surface, and converting the present desolation into a bustling mart of trade" (Wonders, 1974, p.9, Quoting Macoun).

John Macoun mentions steam, again placing dependence on the water

resources of the area and also a bustling mart of trade which will require water. Between the time of Macoun's account until the search for a separation process began Fort McMurray was a community high on hopes waiting for the big breakthrough which would bring people, industry and an economic base.

In the early 1900's a search for commercial uses of the Oil Sands began. Sidney Ells, then working for the Mines Branch of the federal government tried to develop the Oil Sands for pavement of roads in Alberta. This scheme fell through because mining and transportation costs made it too costly to compete with conventional asphalt. In 1920 Karl A. Clark began a long and arduous task of developing the technology necessary for separating bitumen from the sand. Karl A. Clark's process involved the use of large quantities of hot water and steam used in the separation process; this is essentially the process being used by G.C.O.S. (Great Canadian Oil Sands) and modified by Syncrude.

All of the development since the sighting of the oil sand outcrops by Peter Pond has centered around or greatly involved the use of water. Early settlement of Fort McMurray, first as a fur trade center then as a transportation center was dependent upon water for both the wildlife based furs and water transportation. Neither of these uses was consumptive in nature nor did they provide any large scale water quality changes which had detremental repercussions. The "third great hope", the separation of bitumen from sand, requires large quantities of water to be used in the steam separation process. Major changes are required in surface drainage patterns as well as ground water flow systems.

Development on a grand scale will require knowledgeable water management decisions to be made.

CHAPTER III

3.1 Introduction

The regional hydrology is discussed first in this chapter to present a background for understanding the discharge patterns of the larger rivers. Explanation of the hydrology of Ponton and Boyer Rivers is included to give the reader an idea of runoff variation from upland areas versus that from a flat poorly drained lowland area. Pre-construction hydrology is reviewed along with a review of the post-construction hydrology of the Beaver Creek Basin. The final sections of the chapter include an analysis of the yearly hydrographs from 1972 through 1976 and an analysis of the storm hydrograph resulting from nearly 10 centimeters of rain recorded on August 26, 1976.

3.2 Regional Hydrology

The Athabasca River is the main drainage feature in the Alberta Oilsands Region with most of the streams originating in the Oil Sands area emptying into it. The Athabasca River originates in the Rocky Mountains approximately 110 kilometers south of Jasper townsite and flows in an east-northeast direction 1140 kilometers from its origin to its outlet in Lake Athabasca 160 kilometers north of the study area. After leaving the Rockies the river flows in north-easterly direction across the dip of resistant bedrock formations from Buffalo Creek to Fort McMurray with a steep gradient of 1.05 meters per kilometer (m/km).

These resistant bedrock formations have created the Grand, Brule, Crooked and Boiler Rapids. The Athabasca River bends abruptly north at Fort McMurray before its confluence with the Clearwater River and flows north along the strike of bedrock formations with a shallow gradient of .11 m/km. This large change in river gradient combined with the rapids and steeply incised channel have caused major ice jams near Fort McMurray. These ice jams and subsequent flooding are aided by the earlier melt and break-up of the Athabasca River in the southern (plains) part of the basin.

Streamflow records for the Athabasca River directly below Fort McMurray were initiated in 1957 and are continuing. The yearly mean discharge is approximately 2,091,000 hectare-meters per year (Environment Canada, 1974). The low flow of 1,525,200 hectare-meters was recorded in 1968 while the maximum annual discharge was 2,779,800 hectare-meters in 1965. Yearly discharge is highly variable from year to year and also between seasons of the same year. Maximum daily flows, on the Athabasca River, most often occur in early summer while low flow characteristics are most common in early February (MacKay, 1966). Maximum flows are associated with large amounts of winter snowpack in the mountains, relatively late melting of snow in the headwater regions and extensive late spring and early summer rains falling on soils at or near soil moisture storage capacity levels. Minimum flows are associated with the lowest mean temperatures and precipitation (i.e. January and February) along with a continual draw down of ground water contributions and they commonly occur in February and March. A maximum daily discharge

of 4,700 cubic meters per second (m^3/s) was recorded on July 15, 1971 and a maximum monthly discharge of 2,738 m^3/s was recorded for the month of July 1971. A minimum daily discharge of 97 m^3/s was recorded on February 3, 1964 and a minimum monthly discharge of 106 m^3/s was recorded during February of the same year. As a comparative figure, monthly minimum flow on the Athabasca River would be comparable to nearly six times the natural discharge of the North Saskatchewan at Edmonton in December (Environment Canada, 1974). Discharge on the North Saskatchewan has been increased in winter months since construction of the Bighorn Dam upstream from Edmonton. Discharges on the Athabasca River and its major tributaries do not strongly reflect the greater proportional variation noted on Beaver Creek and other smaller streams.

Using existing runoff data it is possible to examine the overall water balance for the Athabasca Oil Sands region. A regional water balance equation would be in the form of:

Precipitation = Evapotranspiration + Runoff (Northwest Hydraulic Consultants, 1975).

In this equation runoff is delimited by the area: regional runoff = Slave River (Fitzgerald) - Peace River (Peace Point) - Athabasca River (Athabasca) - Clearwater River (above Christina) - Fond du Lac River (Stony Rapids). Using this equation regional runoff averages 2,214,000 hectare-meters of water from 15,292,800 hectares of land. This runoff is equal to a water equivalent depth of 14.7 centimeters over the entire drainages. Precipitation is estimated to be 40.6 centimeters over the entire basin in the Northwest Hydraulic Consultants report and the author

believes this is a conservative estimate. Using Longley's material (1972) one would estimate an average precipitation of 43 to 47 centimeters. It is likely that precipitation in the upland areas could be much more than these estimates. Using the precipitation estimates, runoff data, and the equation in the Northwest Hydraulic Consultants report evapotranspiration is estimated between 27 and 32 centimeters. Although much of the area is north of Beaver Creek Basin these estimates are much too low. These estimates of evapotranspiration are nearly 1/2 times lower than estimates made by the author (see section 4.5). No allowance is made for summer deficits which often occur. One is lead to believe that water is never a limiting factor in estimating evapotranspiration. Precipitation should also be increased and this would necessitate increasing evapotranspiration estimates.

Specific patterns of the Athabasca River discharge, in the Athabasca Oil Sands area, are a function of many factors outside of the area (e.g. winter snowfall in the mountains, areal variation over the basin, and variation and intensity of precipitation over northern Alberta). A detailed study of discharge patterns on the Athabasca River would not lead to a better understanding of Beaver Creek discharge patterns. A few general patterns can be noted at the regional level. Rivers east of the Athabasca River north of Fort McMurray drain north into Lake Athabasca and flow through aeolian sand deposits which permit relatively great amounts of infiltration, thus a major portion of stream discharge comes from ground water contribution. This is not true of the upland areas and doubtful for extensive muskeg areas. This stream network

is not as extensive as that of the rivers north of Fort McMurray which drain directly into the Athabasca River. These streams drain areas of largely lacustrine surficial material and tend to have an extensive drainage network. The larger streams are deeply entrenched into the McMurray Formation and have relatively stable channels. Most discharge comes from surface flow with limited ground water contribution.

Many of the rivers of north-eastern Alberta are currently being gauged; the problem is that very few of these streams have more than two or three years of record and only cursory patterns can be determined from these scanty data. Gauging on the MacKay River was instituted in 1972 while seasonal gauging on Beaver Creek was conducted from 1961 to 1966, before continuous gauging began in 1972. One river with relatively useful data, as a comparative tool, is that of the Hangingstone River which empties into the Clearwater River within the townsite of Fort McMurray. Seasonal recording on the Hangingstone River began in 1965 and ended in 1970 when continuous gauging began.

The Hangingstone River Basin has its headwater region 54 kilometers south of Fort McMurray and has a basin area of 1074 square kilometers which is approximately two and one half times larger than Beaver Creek Basin (Northwest Hydraulic Consultants Ltd., 1974). The basin has a northerly aspect with an average slope of 6.4 meters per kilometer. Drainage from the south-eastern end of the basin is coming from an upland area, the Stony Mountain Escarpment, which reaches an elevation of 833 meters. Vegetation consists of sparse spruce stands with local areas of aspen and treed muskeg on the east side of the river with a primary cover

of treed muskeg on the west side of the river (Figure, 1.3). Although vegetation is not as dense as that in Beaver Creek Basin it is of the same species. As in the Beaver Creek Basin there are no large lakes in the basin which would provide significant amounts of detention storage. Precipitation averages 50 centimeters over the basin but due to orographic effect as much as 63 centimeters of precipitation is received on the escarpment yearly (Hallock, 1976). Mean daily discharge is 5.2 m^3/S amounting to 14.2 centimeters of runoff from the entire basin (Environment Canada, 1974). Although the basin characteristics of the Hangingstone River Basin are not identical to those of Beaver Creek Basin many similarities exist such as topographic rise, vegetation, and basin slope. These similarities plus the close proximity of the two basins make comparisons useful when gauged data are used to extend the record for Beaver Creek.

The Ponton and Boyer Rivers are two streams with a long gauging period which exhibit runoff characteristics in Northern Alberta from upland and lowland areas respectively; this variation in flow can be compared with the flow recorded on Beaver Creek and also flow from these two streams serves as proof of the much greater yields of the uplands (Figure 1.1). The Ponton River drains an upland area of 2548 square kilometers with its headwaters flowing from Margaret Lake which is in the Caribou Mountains 900 to 1200 meters above sea level. Upland reaches of the Caribou Mountains are covered by muskeg and stunted black spruce while the better drained flanks are dominated by aspen and white spruce. The Ponton River enters the Boyer River a short distance from its

confluence with the Peace River.

The Boyer River drains a lowland area of 6267 square kilometers between 300 and 600 meters in elevation. The Boyer River Basin is situated south-west of the Caribou Mountains in close proximity to the Ponton River Basin and drains a flat lowland area with poor drainage characteristics. Vegetation in the Boyer River Basin consists mainly of treed muskeg with stunted black spruce; some aspen and grassland covers thrive on the best drained sites (Atlas of Alberta, 1969). Both of these river basins are located approximately 320 kilometers west - north-west of the Beaver Creek Basin.

Total yearly discharge for the Ponton River has been greater than that of the Boyer River in every year since gauging began except in the high flow year of 1974 (Table 3.1). In the driest year, 1970 total yield of the Ponton River Basin was 3.7 centimeters while the yield of the Boyer River Basin was less than 0.1 centimeter in depth. The Ponton basin yield for the 13 year period is 12.6 centimeters per year while the Boyer River yielded only 1.4 centimeters per year during the same period.

Increased precipitation, decreased evapotranspiration and good drainage on the flanks of the Caribou Mountains are the three factors which account for the greater yearly discharge being recorded from the smaller basin. Higher per unit discharge in the Ponton River Basin is provided by increased precipitation is induced by orographic uplift. Very few meteorological stations are located in northern Alberta with none of these being located in the uplands. Scanty precipitation data from the Forest Service of Alberta does serve as an indicator of the increased

Table 3.1: Ponton River Discharge Versus Boyer River Discharge

Hectare Meters per Year (HMY) and Centimeters (Cm)

	Ponton River		Boyer River	
Year	Total (HMY)	Depth Equivalent (Cm)	Total (HMY)	Depth Equivalent (Cm)
1975	46,617	18.2	7,060	1.1
1974	37,761	14.8	38,991	6.2
1973	53,259	20.8	8,105	1.3
1972	22,878	8.9	13,530	2.1
1971	9,594	3.7	845	.1
1970	15,498	6.0	2,363	.4
1969	25,092	9.8	18,696	2.9
1968	31,734	12.4	9,483	1.5
1967	46,617	18.2	3,321	.5
1966	24,354	9.5	2,029	.3
1965	31,611	12.3	2,570	.4
1964	30,996	12.1	5,018	.8
1963	42,927	16.8	2,423	.4
mean	32,226	12.6	8,802	1.4

Source: Environment Canada, Water Survey of Canada, Surface Water Data 1963 to 1975.

precipitation in the uplands. Decreased evapotranspiration may well be major reason for higher yields from the Ponton River Basin. Much of the

Ponton River Basin is located 600 meters above the surrounding land on a plateau like feature in the Caribou Mountains. This change in elevation would suggest that mean temperatures would be nearly 4° centigrade cooler than areas drained by the Boyer River. Thus, evapotranspiration would be greatly reduced during the summer months and evapotranspiration would begin later in the spring and end earlier in the fall. Frost occurring anytime during the growing season would hinder vegetation from transpiring at optimal rates. Although the flanks of the Caribou Mountains are only a relatively small percentage of the total area drained by the Ponton River high yields would be generated from these well drained slopes.

Yearly discharge on the Boyer River fluctuates wildly from year to year. Discharge during the 60's was relatively consistent but the 70's have been characterized by extremes in discharge. Precipitation data for years of maximum discharge on the Boyer River reflect above average snowfall for the winter months followed by above average spring rains. Kellerhals (1974) found that 10 years of discharge data exhibited snowmelt floods in all years on the Boyer River. This is only partially correct; in most years rains in the fall and snowmelt in the spring are used to recharge soil moisture. Vast areas of muskeg in the Boyer River Basin provide a large amount of detention storage; this muskeg intercepts a major portion of the snowmelt and early spring rains in most years and holds this moisture for evaporation and transpiration later in summer. Then in most years a large part of the snowfall is used to recharge the soil and the early spring rains produce the flood flows. Only with heavy

snowfall and heavy spring rains, correctly timed, will the maximum discharges such as in 1969 be observed(table 3.1).

Runoff from the Ponton River Basin per unit area has been greater than that of the Boyer River Basin in all years discharge has been gauged. Runoff from the Ponton River Basin follows the yearly precipitation total more closely than in the Boyer River Basin. Maximum yearly discharges on the Ponton River have not been caused as exclusively by snowmelt in as many years as that of the Boyer River. Rainfall floods are the result of good drainage from the Caribou Mountains compounded by an increase in precipitation with elevation. Greatly decreased evapotranspiration in the uplands permits soil moisture storage levels to remain near capacity levels thus allowing for maximum discharges to occur from moderate summer rains. A similar pattern exists in the tributaries of Beaver Creek which originate in the uplands. A classic example of the rainfall yield of uplands occurred in 1973; the year in which 53,259 hectare-meters of runoff which is the highest yearly discharge on record for the Ponton River. Over 34,000 hectare-meters, or 70 percent of the total runoff was recorded in the months of June, July and August. Precipitation in June was 9.2 centimeters which is 5 centimeters above normal and during July 17 centimeters of precipitation was recorded.[1] Records indicate that the Ponton River showed a rapid response in discharge after the precipitation occurred while the soils of the Boyer River Basin provided storage for the

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[1]All precipitation data used were taken from the Monthly Weather Records of the Fort Vermilion CDA station. This is a lowland station having an elevation of 277 meters above sea level.

less heavy rains.

3.3 Pre-Construction Hydrology of Beaver Creek

Beaver Creek is the most significant hydraulic feature in the study area. It flows a distance of 47 kilometers from its headwaters in the Thickwood Hills to its confluence with the Athabasca River (Figure, 1.2). Beaver Creek, after flowing out of the Thickwood Hills, is a sinuous stream entering a flood plain 366 to 457 meters in width (Syncrude, 1976). After flowing in a northerly direction across Crown Lease No. 17 Beaver Creek bends in an easterly direction flows under Provincial Highway 63 and then drops off the escarpment into a narrow and deeply incised channel (18 meters in depth) before entering into the Athabasca River. Beaver Creek has a slope of 6.1 meters per kilometer originating at a maximum elevation of 530 meters ASL and discharging into the Athabasca River at 232 meters ASL. The Beaver Creek Basin covers an area of 435 square kilometers above the gauging site used for the period 1972 to 1975 (Environment Canada, 1975). The total land area drained by Beaver Creek is estimated to be 460 square kilometers. Beaver Creek Basin has a north - north-easterly aspect with a total relief of 298 meters. Mildred and Ruth Lakes occupy glacial meltwater channels and are the only lakes in Beaver Creek Basin or near the Syncrude operation. Mildred Lake contributes to Beaver Creek via an overflow channel flowing from the northern end of the lake. Ruth Lake is in a separate drainage basin with an overflow channel into Poplar Creek.

Few data are available with respect to discharge patterns on Beaver

Creek; seasonal data are available for the period June 1961 to October 1965 while continuous gauging began in April of 1972. Mean daily discharge is 1.8 cubic meters per second (CMS) which provides a mean annual runoff of 3,542 hectare meters (Northwest Hydraulic Consultants, 1975). Yearly discharge has varied from a low of 2,214 hectare meters in 1976 to a high of 7,121 hectare meters in 1974.[1] Comparisons of total runoff in hectare meters and depth of runoff equivalent over both the Beaver Creek and Hangingstone River Basins are presented in table 3.2.

Although data are limited to four years of runoff, for comparative purposes, the Hangingstone River Basin contributes more runoff per unit area in three of the four years. Fluctuations of yearly discharge for Beaver Creek and the Hangingstone River appear to correlate well. For the four years of data, discharge from the Hangingstone River is approximately 50 percent greater per unit area than that of Beaver Creek Basin. Runoff has varied from 11.3 to 16.4 centimeters over the entire basin. In 1972 Beaver Creek Basin had greater runoff per unit area than the Hangingstone River Basin. This is understandable for some years with more favorable combinations for runoff in one basin than another. Runoff per unit area is relatively small in the boreal forest zone of northern Alberta, hence a heavy precipitation event timed properly falling over the Beaver River Basin and not the Hangingstone River Basin could have provided the additional runoff in 1972. Using the Hangingstone River data as

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[1]Data from 1972 does not include discharge from January, February, or March. Even a high estimate of 25 hectare meters per month for each of the three months would not alter the premise.

Table 3.2: Beaver Creek and Hangingstone River Yields*

	Beaver Creek		Hangingstone River	
Year	Total Yearly Discharge Hectare Meters	Depth of Runoff in centimeters	Total Yearly Discharge Hectare Meters	Depth of Runoff in centimeters
1975	16,027	13.9	16,728	18.8
1974	15,473	12.6	16,236	18.3
1973	7,121	16.4	20,418	23.0
1972	2,472	11.3	9,483	10.6

* Source: Environment Canada, 1972-1975.

an indicator, a yield estimate of 20 centimeters of runoff may be made for the Beaver Creek Basin for 1970.

Elevation is the most important factor when considering the difference in per unit area discharge between the Hangingstone River Basin and Beaver Creek Basin. Data from the forest lookout stations have proven that there is a significant increase in precipitation with increase in elevation in north-eastern Alberta (Environment Canada, 1945-1975). Hallock (1976), in his water balance equation and using Lookout Station and Radar Station data estimated annual precipitation to have been 63 centimeters near the top of the Stony Mountain Escarpment while Fort McMurray had an annual average precipitation of 44 centimeters. Potential evapotranspiration was estimated to be 6 centimeters lower on top of the Stony Mountain Escarpment. Using the increased precipitation and

decreased potential evapotranspiration in the water balance equation a large yield difference results. Yields on top of the escarpment are nearly 23 centimeters while the Fort McMurray airport area provides an average yield of 2.5 centimeters.

One other variable which provides for the larger per unit area discharges in the Hangingstone River Basin is the form in which precipitation falls (Chow, 1964). Having a greater elevation than that of Beaver Creek Basin allows for more of an orographic increase in snowfall, in the Hangingstone River Basin, which allows for greater yields and longer sustained flows in the spring because of the slower snowmelt. Approximately 30 percent of the Hangingstone River Basin lies above an elevation of 600 meters ASL while more than 80 percent lies above 420 meters ASL (Northwest Hydraulic Consultants, 1975). In comparison none of the Beaver Creek Basin lies above 525 meters ASL while only 30 percent lies above 420 meters ASL.

Monthly mean discharge from Beaver Creek is highly variable from month to month and also in the same months in different years. The lowest monthly discharge occurred in March of 1975 when 21.5 hectare meters of discharge was recorded while in May of 1972, 2509 hectare meters of runoff was recorded. The maximum discharge of May 1972 amounted to nearly 50 percent of the total discharge of that year. The month of maximum discharge is almost as variable as the discharge itself; yearly monthly maximums have occurred between May and September inclusive. Variability in discharge, whether it be daily, monthly, or yearly is a characteristic common to most streams in northern Alberta. The amplitude of variability

is greatest for the smaller streams and rivers and decreases for the larger rivers.

3.4 Post-Construction Hydrology

Before any attempt can be made to analyse the yearly and seasonal hydrographs, alterations within the Beaver Creek Basin must be reviewed. Construction of a plant and mining operation such as Syncrude is impossible without substantial surface disturbances. Before construction began a plan was initiated to develop a site which would have an internal drainage system.

The old channel of Beaver Creek runs through the center of the project, but a dam cutting off flow was constructed at the southern end of Crown Lease No. 17 (Figure 1.3). Water from Beaver Creek has been diverted into the Athabasca River via Ruth Lake and Poplar Creek.[1] This diversion has created a new reservoir on Beaver Creek which is connected to Ruth Lake via a ditch and natural drainage through muskeg. Attempts to dynamite a channel extension during the winter of 1976-77 were unsuccessful as the muskeg absorbed the shock. Water supply for the plant operation will be provided by the Athabasca River; during the early years of operation all water will be supplied by the Athabasca River but some recycling will take place in later stages of development. Mildred Lake has been eliminated from the Beaver Creek drainage to act as a storage reservoir for fresh water supply. This necessitated raising lake levels 4 meters by

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[1]Further discussion of the hydrology of Ruth Lake and Poplar Creek can be found in a thesis by Waddell in preparation.

constructing a dam at both the north and south ends of the lake. Northerly surface drainage from the mine and plant site in the old Beaver Creek channel has been halted by the construction of the tailings pond at the north end of Crown Lease No. 17.

Between Beaver Creek Dam at the southern end of lease 17 and the tailings dyke at the northern end of the lease, four tributaries formerly flowed into the developing part of the lease site. These four tributaries have been diverted northward, west of the mining and plant site, by construction of the west interception ditch. Flow from the west interception ditch is routed north around the project site into the Athabasca River via Bridge Creek. After construction of the west interception ditch an earthen dam was placed across the ditch directly upstream from Creek 4 to divert these waters south and east into the Beaver Reservoir. This new diversion necessitated the construction of a channel from the southern end of the west interception ditch into Beaver Reservoir. This diversion of Creek 4 was necessary to prevent ponding west of the interception ditch as Creek 4 is at a lower elevation than the west interception ditch. Diverting Creek 4 will provide additional yield for Beaver Creek Reservoir which may be needed for adequate disposal of saline waters.

In summarizing the post-construction hydrology, it can be shown that three major man-made features give rise to modification of the drainage on the project site. Firstly by damming Beaver Creek at the southern end of Lease 17 halted flow across the project site. Secondly, the tailings dyke prevents runoff from leaving the project site in the natural direction of flow. Finally, tributaries which at one time entered the project site

from the west have been diverted northward via the west interception ditch. Changes in water yields relating to changes in surface patterns may be at least as significant as the construction features (for further discussion see section 5.3). These developments have all been built as part of Syncrude's water management policy which has been described as: "Syncrude's operating philosophy with respect to runoff is to contain and use all water flowing from disturbed and developed land; runoff from undisturbed land is redirected to the natural environment wherever possible" (Syncrude, 1976).

3.5 Yearly Hydrograph Analysis

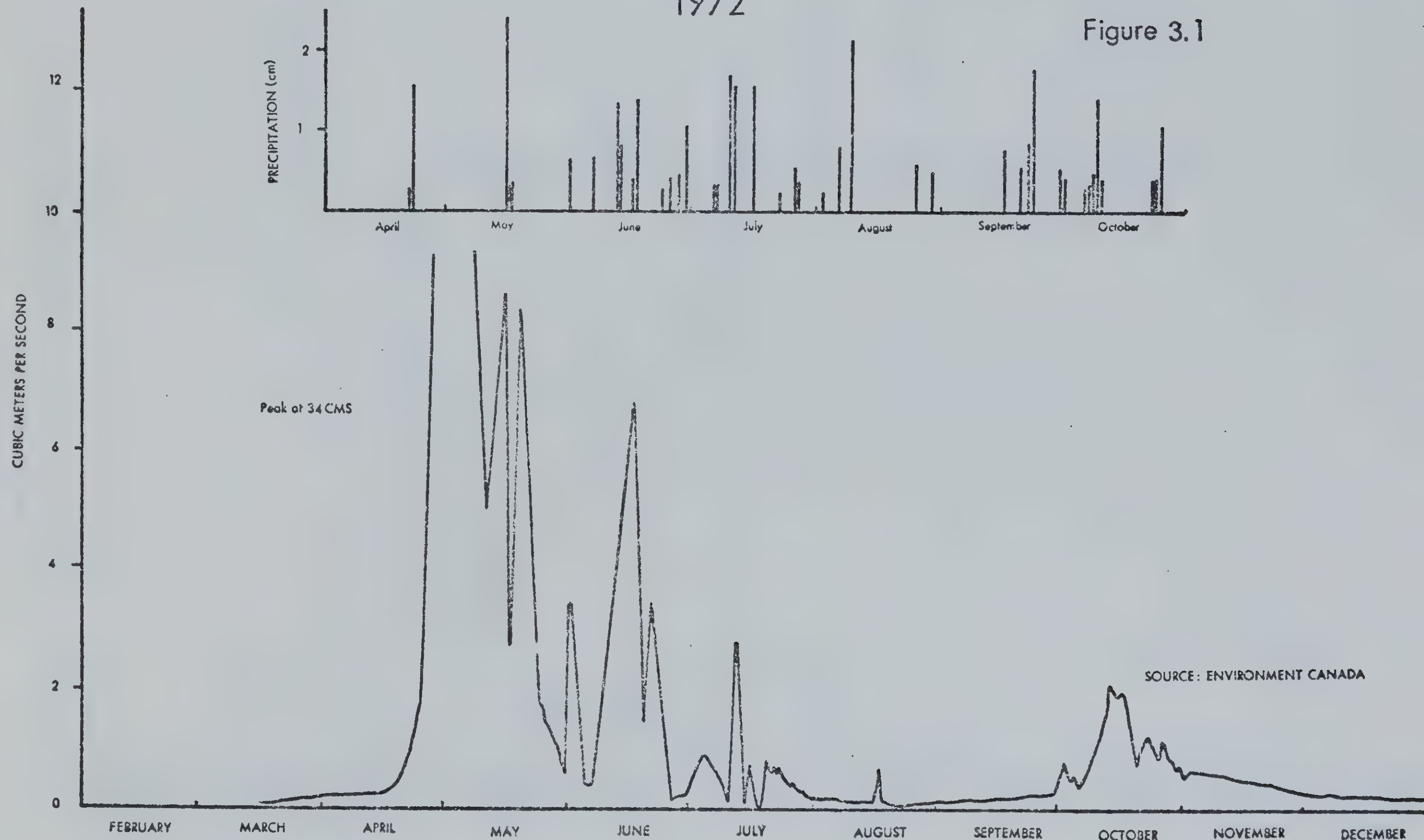
Discharge from Beaver Creek, as has been shown previously, is highly variable from one year to the next as well as from one day to the next. A combination of factors ranging from soil type to precipitation patterns accounts for this variability. Discussion of the most important factors may be used as a basis for analysis of the hydrographs using the four years of runoff data collected before construction of Beaver Creek Dam changed the drainage system. Runoff, gauged as it flows out of Beaver Creek Basin, consists of surface runoff (i.e. overland flow), subsurface runoff (i.e. interflow), and ground water runoff (Chow, 1964). In analysing the yearly hydrographs quantitative estimates of the component parts of runoff were not undertaken as little work has been done to define the local flow systems in the Beaver Creek Basin. Analysis of total runoff was done using the hydrographs in figures 3.1 to 3.5.

The runoff cycle for a particular storm hydrograph can be divided

BEAVER CREEK DISCHARGE HYDROGRAPH

1972

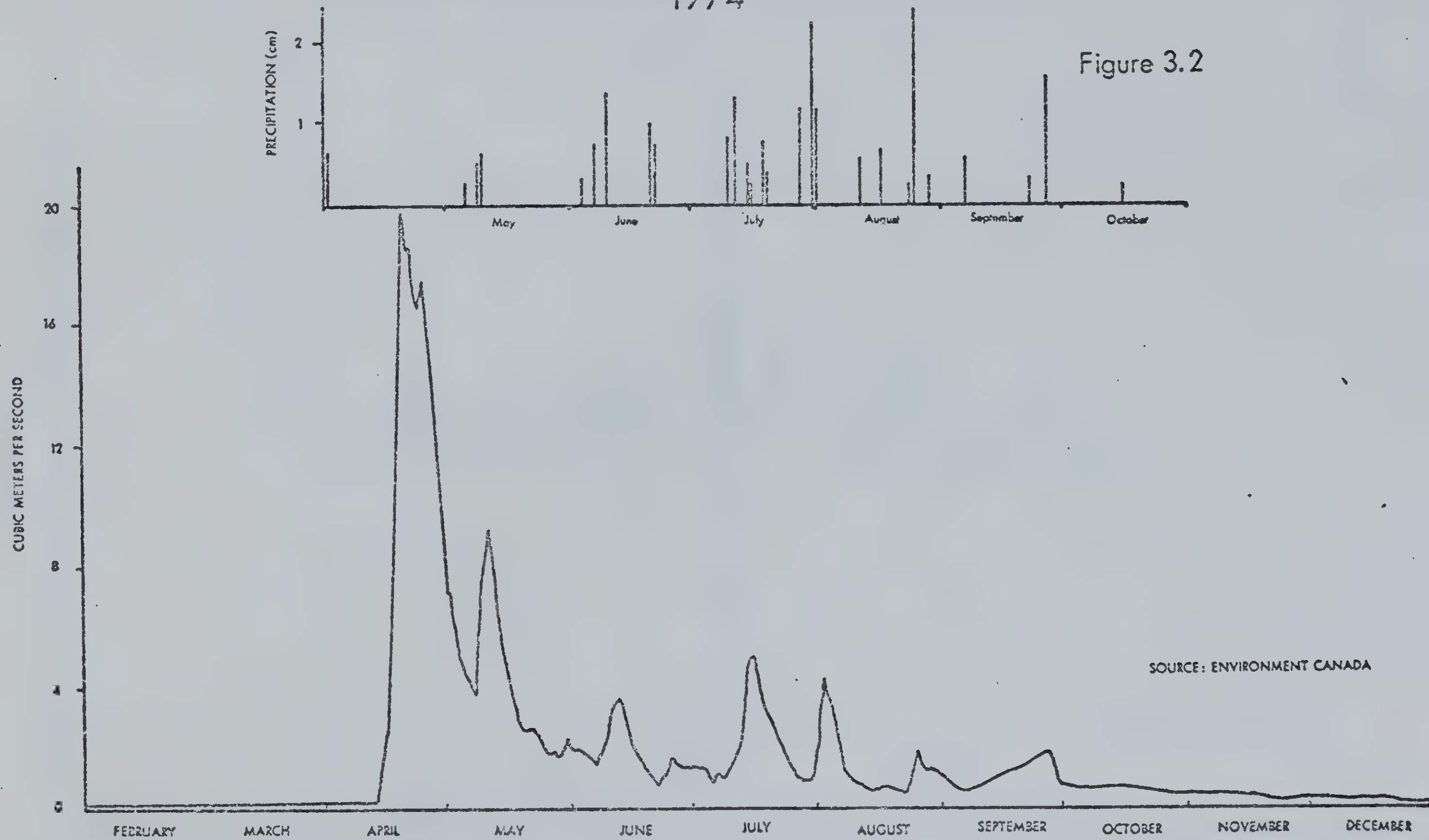
Figure 3.1



BEAVER CREEK DISCHARGE HYDROGRAPH

1974

Figure 3.2



BEAVER CREEK DISCHARGE HYDROGRAPH

1975

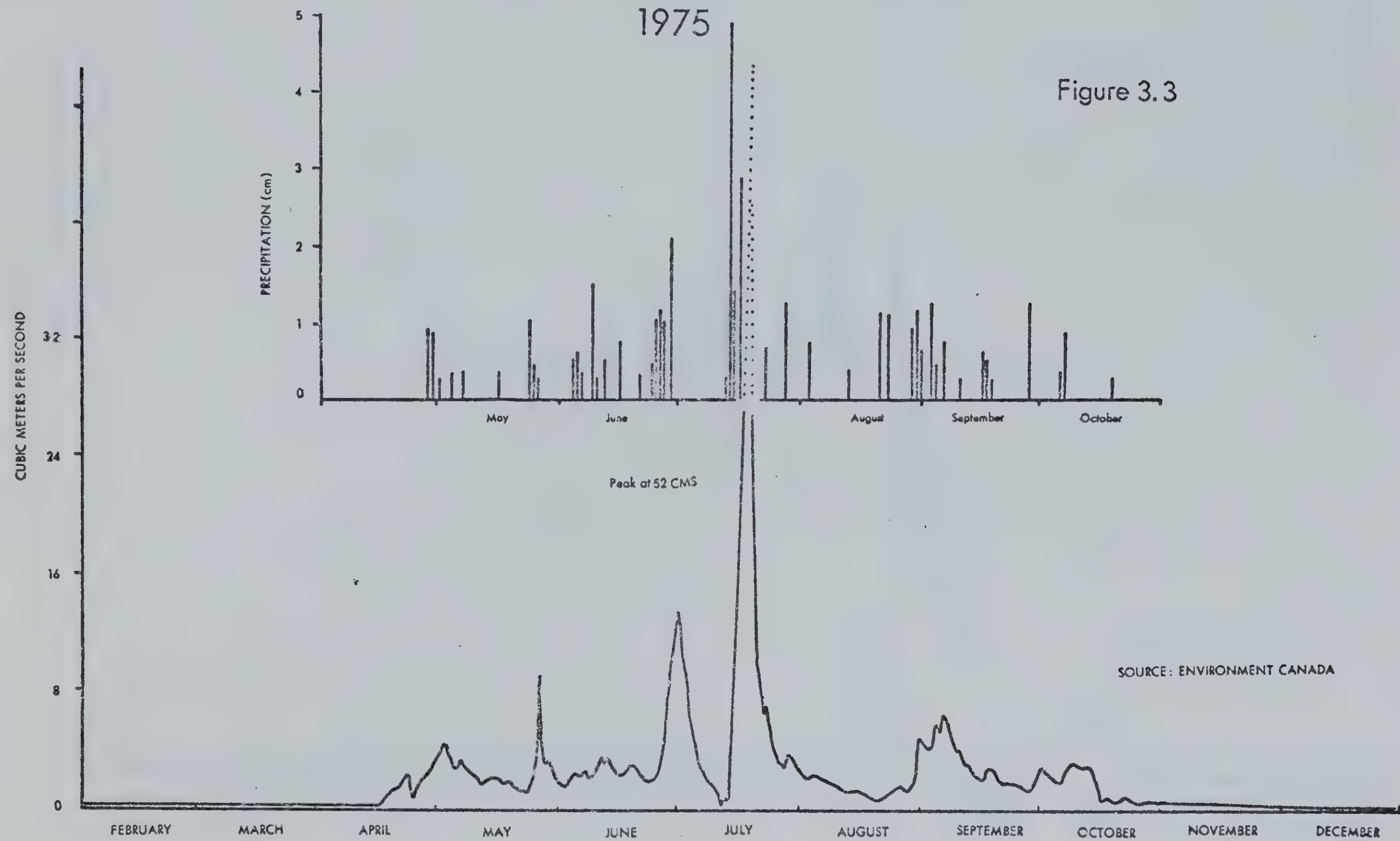
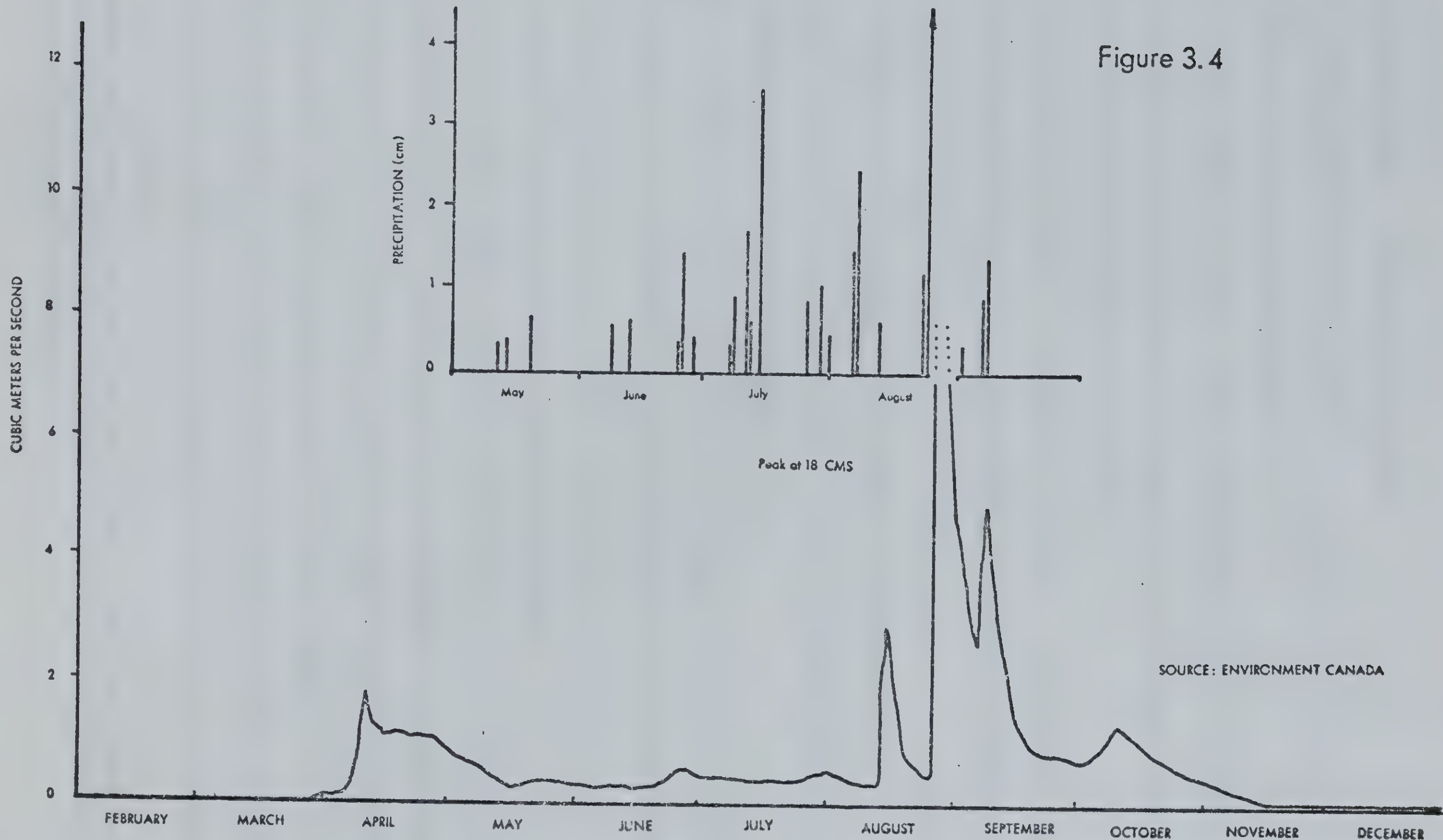


Figure 3.3

BEAVER CREEK DISCHARGE HYDROGRAPH

1976

Figure 3.4



SOURCE: ENVIRONMENT CANADA

into five major steps. In summary these are:

1) rainless period before rainfall - an extended dry period with ground water contribution low.

2) initial period of rain - enters the runoff cycle as channel precipitation, intercepted by vegetation, infiltrates the soil, or retained in surface depressions.

3) continuation of rain of variable intensity - interception peaks, retention storage no longer possible, if rainfall intensity is greater than infiltration overland flow begins. If stream flow rises rapidly, a change from effluent to influent stream condition takes place, as a result the stream contributes to ground water and bank storage.

4) continuation of rainfall - natural storage filled while infiltration rate approaches the rate of ground water transmission. Ground water table rises until groundwater contribution to stream flow equals maximum recharge possible.

5) termination of rain - channel storage and surface retention become depleted. Evaporation and transpiration are occurring. Streamflow is sustained by releasing water from stream channels, subsurface flow and ground water flow (Hoyt, 1916). [1]

This five phase model of the runoff cycle was used as a basis for subjectively analysing individual storm hydrographs which occurred in Beaver

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[1]Hoyt's model was used to analyse the individual storm hydrograph and in the thesis this model is used to describe individual storms noted on the yearly discharge hydrographs.

Creek Basin.

There are three yearly patterns of discharge maxima which have occurred since 1972. These three patterns can be classified as:

1) snowmelt maxima - occurs in the months of April and May with greatest percentage of the peak caused by melting of snow, especially if soil moisture recharge was above normal in the previous fall.

2) rain on snowmelt maxima - precipitation combines with snowmelt to produce the yearly maximum discharge.

3) rainfall maxima - most common in the months of May to August with substantial precipitation, often exceeding the infiltration and/or storage capacity of the soil.

A rain or snow maximum occurred on April 29th, 1972 when a peak of 34 CMS was recorded. Average precipitation in November and December of 1971 was accompanied by above average precipitation in the first 4 months of 1972. Snowfall for the period January through April accumulated to a depth of 190 centimeters which had an estimated water equivalent of 15.3 centimeters compared to an average of 7.6 centimeters for the same period. The snowmelt runoff began rapidly as evidenced by the steep slope of the rising limb of the hydrograph (Figure 3.1). Precipitation totalling 1.6 centimeters on April 21, 1972 may well have been the triggering mechanism providing the rapid runoff and steeply sloped rising limb of the hydrograph. Specific analysis of the effect of precipitation on snowmelt can only be determined if such factors as condition of the snowpack and temperature of the rainfall are known. An excellent discussion of all the

factors of rain on snow peak discharges can be found in Snow Hydrology (Army Corp of Engineers, 1956). The recessions on May 5 and 6 was the result of another freeze taking place between May 4 and 6. A secondary maximum of 9.3 CMS was recorded on May 18th; this peak was the result of less than 1 centimeter of precipitation on May 15 and 16. Rapid and variable peaking occurred into mid-June as most soil moisture storage levels were at or near capacity levels. During late-spring and early summer with high soil moisture levels, it took only light showers to reach stages (3) and (4) of Hoyt's runoff cycle. All stages of the runoff cycle occurred but (1) and (2) were of short duration for each storm hydrograph. Precipitation in July produced peaks of relatively minor flow in comparison with the peaks in May and June even though precipitation was quite extensive. Much of the precipitation in late summer months went into soil moisture storage. By late August phase (5) of the runoff cycle is reached from the storms of late July and discharge levels of .5 CMS can be attributed to ground water flow with the possibility of a limited amount of interflow.

A snowmelt maximum is depicted by the 1974 hydrograph of Beaver Creek (Figure 3.2). The only significant precipitation event in April occurred before the snowmelt on the 2nd and was in the form of snow as the mean temperature for the day was -2°. The snowmelt period extends over a longer period than that of 1972 and may be partially attributed to the gradual rise in mean temperature through April. A secondary peak, accentuated by the early May precipitation occurs on May 10 but soil moisture storage levels were low by then causing a reduction in the

magniture of the peak compared to comparable situations in 1972. Moderate rainfalls in late July produced limited discharge maximums because soils in the basin were relatively dry. An interesting difference noted in 1974 not occurring in 1972 is that minimum discharge levels were higher in 1974 than corresponding levels of late summer 1972. Even distribution of precipitation was most likely responsible for keeping discharge above the .5 CMS level in 1974.

A rainfall maximum is evident in the discharge hydrograph of Beaver Creek in 1975 (Figure 3.3). A relatively small peak discharge occurred in late April to early May and consisted of both snowmelt and rain. A slow snowmelt coupled with light precipitation during the previous winter accounted for the low discharge peak of less than 3.0 CMS on April 23. This long melting period provided one of the conditions necessary for a great percentage of the snowmelt to infiltrate the soil (Ward, 1967). The radiation balance of the snowpack determines the speed of the melt; discussion of these melting patterns can be found in a thesis titled "Water Balance of Cooking Lake Moraine" (Woodburn, 1977). These relatively large amounts of infiltration set the stage for the 10 CMS discharge recorded on May 26 as a result of the moderate rains during the third week in May.

Hydrograph peaks during 1975 exhibit very steep rising and recession limbs much like those of an urban watershed. This rapid peaking was caused by the construction of a dam across Beaver Creek at the north end of Lease 17. This artificial reservoir would provide storage for light rains especially in late summer but there was insufficient storage for

major rains. In June well distributed rains filled detention storage of small sloughs and water bodies, added to soil moisture storage, and filled the artificial reservoir on the lease site. In a period of 4 days from July 13 through 16 a total of 7.5 centimeters of rain fell over Beaver Creek Basin. Flashy runoff from the cleared mining and construction site combined with runoff from the rest of the basin provided enough water to rupture the dam and produce a maximum yearly discharge of 55 CMS on July 17. Hydrograph peaks in September of 1975 do not exhibit the flashy characteristics typical of those which occurred in early summer because some soil moisture storage was provided in the fall.

A rainfall maximum occurring in late August is the most striking feature of the 1976 hydrograph (Figure, 3.4). No flow was recorded in Beaver Creek from early January until early March as ground water contribution was depleted. A relatively small snowmelt runoff peak of 2 CMS was recorded on April 12, 1976. A light winter snowfall coupled with less than 1 centimeter of precipitation during April provided for the lowest snowmelt peak recorded during the period 1972 through 1976 (The snowmelt peak of 1977 will probably be comparable to that of 1976). Early and midsummer 1976 was very dry and a low stage of discharge of 0.5 CMS was maintained until a peak of 3 CMS was recorded on August 14. A yearly maximum discharge of 18.5 CMS was recorded on August 29, 1976 after 11.4 centimeters of precipitation was recorded from August 25 through August 28. This late August peak was very flashy in response rising from .6 CMS on August 26 to 11 CMS the following day.

CHAPTER IV

Water Balance Procedures

4.1 Introduction

Discussion in this chapter includes a review of the water balance using Thornthwaite procedures and a development of the water balance concept. Previous tests and uses of the water balance approach are discussed in section 4.3 with emphasis on western Canadian studies.

A literature review of the most popular methods for determining potential evapotranspiration (referred to as consumptive use incorrectly by some authors) is included in sections 4.3 and 4.4. Emphasis is placed on the Thornthwaite and Penman techniques, as they are the two major techniques used to estimate potential evapotranspiration in this thesis. In Section 4.5 covers a comparison of potential evapotranspiration results using these techniques with a discussion of all the water balance equation inputs needed.

In the last section (4.6) the water blance equation for Fort McMurray is discussed. Adjustments are made and a water balance equation for the study area is presented.

4.2 Thornthwaite Technique

C.W. Thornthwaite was the first climatologist to develop a useful procedure for calculating the water balance by involving potential evapotranspiration. Previously the water balance had been: precipitation=

evapotranspiration + surplus ± storage change but evapotranspiration is very unsatisfactory unless associated with deficit as in potential evapotranspiration - deficit = evapotranspiration because regional gradation with temperatures are not possible. When temperature plus daylength is expressed in terms of potential evapotranspiration and thus temperature and precipitation are both expressed in common units so that they can be related, a much more useful balance is obtained. He and Mather (1955, p. 23) defined a yearly water balance as follows:

> when the potential evapotranspiration is compared with the precipitation, and allowance is made for the storage of water in the ground and its subsequent use, periods of moisture deficiency and excess are clearly revealed and an understanding of the relative moistness or aridity of a climate is obtained. If the amount of precipitation is always greater than evapotranspiration, the soil will remain full of water and a water surplus will occur. On the other hand, if precipitation is always less than the potential evapotranspiration or water need, moisture will be limited and a moisture deficit will exist. Under normal conditions both of these conditions will occur during the course of a year or several years at a place so that a comparison of the potential evapotranspiration with the precipitation will show both a wet or a cold season in which water need is less than the available precipitation and a dry or hot season in which the water needs exceeds the precipitation. Under such circumstances there usually occurs a period of full soil moisture storage when precipitation is greater than the moisture demand and a moisture surplus accumulates; a drying period, when the moisture in the soil is used by the plants, the soil moisture storage is diminished and a moisture deficit occurs; and a re-moistening season, when precipitation exceeds water use and the soil moisture storage is replenished. The values of moisture surplus and deficiency as well as the other factors of the water balance can be computed by means of a simple water balance bookkeeping procedure.

In the preceding passage Thornthwaite and Mather repeatedly mentions potential evapotranspiration which is a concept Thornthwaite

developed. In an article titled "An Approach Toward a Rational Classification of Climate" Thornthwaite (1948, p.55) stated that "the sum of the climatic elements that have been under observation does not equal climate." This concept of potential evapotranspiration had been given very little consideration before 1940 by climatologists in their efforts to more closely define the climate of a place. Thornthwaite realized that we have reasonably good records of precipitation and stream discharge from many populated areas of the world but data on evaporation measurements are hopelessly lacking. In fact, theories dealing with the processes and measurement of evaporation and transpiration are still being tested. Thus, in Beaver Creek Basin estimates of potential evapotranspiration may be a very difficult parameter to accurately estimate. These estimates are needed to compute the water balance which is a better indicator of the climate in the study area.

Although the water balance concept was first developed as a climatic tool to determine the relative moistness or dryness of a place there are many potential uses for this approach. By having access to: 1) daily and monthly precipitation totals; 2) water retention capacity of the soil within the root zone, and 3) measured or calculated values for daily and monthly potential evapotranspiration, other dependent variables in the water balance formula can be calculated by bookkeeping procedures (Kakela, 1969). By using the formula, water deficiencies, water surpluses and changes in moisture stored in the soil can be studied. Deficiencies are referred to as drought while water surpluses refer to runoff as overland flow as well as seepage to ground water. Water retention storage capacity

of soils has been determined in previous studies such as (Colman's 1948). Thornthwaite developed tables through the use of empirical relationships, for computing potential evapotranspiration by using standard meteorological data. If the potential evapotranspiration is known, the residual quantity of actual evapotranspiration needed for the water balance procedure can be determined (Potential Evapotranspiration - Deficit).

The water balance technique can also be used to estimate historical data, such as runoff and potential evapotranspiration, if the standard meteorological variables of precipitation and temperature are available. Water balance techniques can be used to expand the data base of areas which have only limited observations. Muller (1972) found that because of growing concern of the environment, complex models are being developed to trace energy, water, and nutrient flow through river systems. He used the Thornthwaite water balance model as a system of components which were used for regional inventory and analysis.

Finally, the water balance technique can be used to adapt to any vegetation or soil moisture condition by adjusting the value used for soil moisture (Thornthwaite, 1946). As mentioned before, the water balance approach lends itself to the hydrologist and soil scientist as well as having relevant use in the field of climatology. The water balance approach is especially suited for studying water resource problems in geography as any of the constituent parts can be examined as they vary in a spatial and temporal context and as Muller (1972, p.168) stated: no single component is superior for hydroclimatic evaluation." One of many references which includes discussion on the type of information which

can theoretically be derived from the water balance procedure is contained in "Snow and the Thornthwaite Water Balance." (Kakela, 1969).

The water balance approach, for all its practical applications, is not without its problems. Measurement techniques applied to actual evapotranspiration have been developed with limited success but measurement of potential evapotranspiration is much more difficult. The difficulty of measuring potential evapotranspiration is caused by the fact that "since it (potential evapotranspiration) does not represent actual transfer of water to the atmosphere but rather the transfer that would be possible under ideal conditions of soil moisture and vegetation, it usually cannot be measured directly but must be determined experimentally." (Thornthwaite, 1948, p.56). This experimental design along with the empirical nature of the formula has led to criticism of the technique by many researchers. It is understandable that if an empirical formula is going to be used over a wide range of latitudes and climates with any degree of accuracy adjustments must be made for different localities. These may include adjustments of precipitation, temperature, evapotranspiration, and areal variations in soil moisture storage levels and for different phases of each.

Since potential evapotranspiration is the most difficult input to measure in the water balance approach, discussion will be centered upon techniques used to measure potential evapotranspiration for use in the water balance. Solar radiation, air temperature, wind, and atmospheric humidity are all factors which have been shown to influence potential evapotranspiration rates. Solar radiation provides the predominant source of energy available for potential evapotranspiration as well as for most

other energy uses on the earth's surface. Thus, many researchers believe that measurement of solar insolation can be used as an index for estimating potential evapotranspiration. Thornthwaite found that there was a close correlation between air temperature and transpiration rates (Thornthwaite, 1948). He argued that changes in solar insolation, wind, and atmospheric humidity were reflected by proportional changes in air temperature. Thus, Thornthwaite's technique is based on an empirical relationship correlating mean monthly temperature and potential evapotranspiration using a standard month of 30 days each having 12 hours of possible sunshine. A daylength adjustment factor has been applied to make allowances for season and latitude as far as 50° N & S latitude (see section 4.5 for further discussion). Most researchers will agree that the Thornthwaite procedure provides reasonably accurate results in the temperate continental zone of the United States. Chang (1974) is a vehement supporter of the theory that temperature is not a good indicator of potential evapotranspiration. He bases his argument on a study conducted near Waynesville, North Carolina in which consumptive use of water by alfalfa, measured in a weighing lysimeter, was very high on a given day and on the following day consumptive use of water was only marginal. Air temperature was the same on both days thus he concludes that temperature is a poor indicator of potential evapotranspiration.

Another argument Chang provides is that air temperature lags behind solar insolation which causes a subsequent lag in the estimation of potential evapotranspiration. This argument would only be a cause for major concern if a short duration water balance was being computed in early

spring or late fall. In early spring estimates of potential evapotranspiration would be low because temperature would lag behind solar insolation. Part of the excess solar insolation would be used to melt ice and snow and therefore potential evapotranspiration estimates would not be as low as some researchers believe. In the late fall, potential evapotranspiration is greater than expected as solar insolation declines rapidly while temperatures remain relatively high thus potential evapotranspiration estimates are high. The author wants to stress that in most empirical studies used to estimate potential evapotranspiration greater accuracy is obtained using a longer test period. This is one of the limitations of the water balance approach which must be realized.

4.3 Previous Tests and Uses of the Thornthwaite Water Balance

The water balance approach has been used widely to map potential evapotranspiration patterns as well as water surplus and deficit patterns. C.W. Thornthwaite, J.R. Mather and D.B. Carter (1958) constructed three maps portraying the water surplus and deficit patterns in eastern North America, with potential evapotranspiration patterns also included. In his work for the Prairie Provinces Water Board, Laycock mapped water deficit and surplus patterns in the Canadian Prairies (Laycock, 1967). Sanderson and Phillips (1969) used the water balance approach to map surplus patterns for the whole of Canada. In a more recent study Muller (1976) used the water balance approach to evaluate whether the frequency and magnitude of high and low flow stages of discharge had changed in the

Mississippi River Basin above Vicksburg.

Another important use of the water balance approach is in the estimation of stream flow. Thornthwaite and Mather (1955, pp.48) wrote that:

> Since the moisture surplus as computed from the bookkeeping procedure represents water that is available for stream flow it is possible to obtain estimates of this latter parameter from climatic data alone. Thus, the procedure enables one to determine stream flow in areas where no stream gauge records exist. If such records are available the information can be used as a check on the validity of the bookkeeping approach. Of course, all of the moisture available for runoff in a month will not be lost in that month for there will be some detention of moisture on the watershed past the end of the month.

Thornthwaite and Mather (1955) cite many examples of areas throughout the United States where their water balance approach has correlated closely with gauged stream discharge. In the eastern United States Thornthwaite and Mather used the water balance approach to provide maps showing the average annual surplus in inches. Discharge measurements of the United States Geological Survey were used to provide maps of runoff, in inches, over the eastern United States and they very closely resemble those constructed using the water balance approach. Results of the water balance approach, when applied to three watersheds near Coshocton, Ohio provided accurate data (Thornthwaite and Mather, 1955). The water balance approach was applied to basins in the Tennessee Valley as well as parts of Virginia and after analysing the data Thornthwaite and Mather (1955, p.49) wrote: "Monthly and annual computed values of runoff are, however in good agreement with measured values and average values . . . based on the series of years investigated they are almost identical."

The water balance approach has been applied in Western Canada with

reasonable results. Laycock (1957) used the water balance approach to outline the approximate patterns of precipitation and stream flow in eastern slopes of the Canadian Rockies and suggest water shed management alternatives which affect the patterns outlined. Many of the basins do not have stream gauging records to check the accuracy of the water balance approach but total aggregate yield from the larger basins did provide close agreement between estimated and gauged yield. A.H. Laycock (1967) used the water balance approach to map water deficiency and surplus patterns in the Prairie Provinces. In this report Laycock suggested that in the drier years when little if any surplus is estimated using the water balance approach it may be necessary to make adjustments in the water balance. Even in the driest years runoff is provided by melting of drifted snow and rapid snowmelt on frozen or partially frozen soil thus having a low infiltration capacity. In a hummocky disintegration moraine area of central Alberta Laycock (1971) has shown that a close correlation exists between surplus and deficiency patterns and lake level fluctuations as determined by the water balance approach. Woodburn (1977) used the Thornthwaite water balance approach in an attempt to more closely define snowmelt runoff patterns as affected by vegetation and land-use changes. A dry year followed by below average snowfall in the winter of 1973-74 provided very little runoff as soil moisture storage levels were never filled to capacity. Runoff which did result was provided by drifting in shelter belts and road ditches and it was necessary to make adjustments in the water balance equation.

Closer to the author's study area, Hallock (1976) applied the water

balance approach to estimate water yield and regime patterns in the Gregoire Lake Basin south of Fort McMurray. Hallock found that discharge recorded from Surmont Creek correlated more closely with the water balance approach after adjustments were made for increased precipitation and decreased temperature due to topographic rise in the upper basin. Computed runoff was checked against gauged runoff during the spring and summer field season of 1975; cross checks were made possible using data collected by Water Survey of Canada in the Hangingstone River adjacent to Gregoire Lake Basin.

Kakela (1969) used the water balance approach in studying snowmelt runoff in Pocket Lake Basin, a subarctic basin north of Yellowknife, North West Territories. Until adjustments were made Kakela found poor agreement with calculated data as compared to gauged discharge on the Yellowknife River. Higher correlations of discharge were obtained by allowing for a time lag between precipitation and materialization of stream flow. Kakela also found that there were wide discrepancies in the retention storage capacities of different sites, thus some sites were contributing twice the mean rate of surplus. Dingman (1966) conducted a study in a subarctic basin in Alaska and found great lag times between precipitation and runoff and suggested that there are different retention problems in organic material not common in most soils.

Although not without its problems the Thornthwaite water balance approach should yield good results in the study area. Previous tests in western Canada have provided useful results. Some modifications will be made as suggested by Laycock (1967, 1971 and personal communication),

Blackwell and Stickling (1958) and Muller (1972).

4.4 The Penman Technique

H.L. Penman (1948) devised a method for estimating evaporation from open water surfaces and then a conversion factor was used to estimate what he calls potential transpiration from vegetative surfaces. Chang (1974) stated that the equation was constructed using sound physical principles, therefore it is not an empirical tool.

The formula consists of two parts; one is taken from the turbulent transfer theory and the other uses the energy balance concept. The equation is in the form: $E = (^{\Delta}/\gamma\ H + E\alpha)\ /\ (^{\Delta}/\gamma + X)$ (Penman, 1948). A complete discussion of the equation and data yielded are provided in section 4.5. Computation of $E\alpha$ is derived from the turbulent transfer approach and is a measure of the drying power of the air involving both wind speed and saturation deficit. The value of (H) is based on the energy balance approach and is largely dependent on net radiation available for evaporation and heating. The ratio $^{\Delta}/\gamma$ is dimensionless and is, in effect, a factor which scales the relative importance of net radiation (H) in the equation (Ward, 1967). Hence, the relative importance of $E\alpha$ increases with large saturation deficits and high wind speeds. During the summer months when evaporation is greatest the net radiation term (H) is given more weight in the equation because $^{\Delta}/\gamma$ increases with increased air temperature.

Owing to its complex formula and need for specific meteorological data, the Penman equation has been proven to provide reasonable results in

many areas of the world. In a literature review of studies comparing the Penman and Thornthwaite techniques of estimating evapotranspiration Penman's method was found to be more accurate except in North America (Chang, 1974). In Minnesota, Baker (1958) has shown the Thornthwaite technique to be superior, while a study in Missouri has shown the two techniques to work equally as well (Decker, 1962).

There has been very little documentation in usage of the Penman technique in areas with climatic and vegetative conditions similar to those found in northern Alberta. Verma (1968) used the Penman method to compute potential evapotranspiration in a study area just north of Edmonton. Verma felt that Thornthwaite procedures overestimate potential evapotranspiration when compared to the Penman method. Since he was interested in soil moisture retention capacities the data were not used in a water balance context, therefore no checks against stream discharge were used to verify the accuracy of either method. Hobbs and Krogman (1966) compared Blaney - Criddle, Penman, and Thornthwaite techniques in an alfalfa field in Vauxhall, Alberta. They concluded that potential evapotranspiration estimates were seriously low using the Penman method using crop factors of .7 for September and .8 for the other months. Potential evapotranspiration estimates in September using the Penman method provided the worst underestimates compared to the rest of the year. The Penman equation also provided a comparatively low (.878) correlation with local data. The author believes that Ward (1974, p.49) best analysed the Penman method when he stated: "although its comprehensiveness implies that the formula constitues a more realistic approach to the estimation of

potential evapotranspiration, it is no less empirical than many of the formulae which have previously been discussed", (i.e. referring to the Thornthwaite and Blaney and Criddle methods). This is especially true if local data must be estimated.

4.5 Other Empirical Methods

Although the Thornthwaite and Penman methods for estimating potential evapotranspiration have been the most widely used many other methods have been developed. Blaney and Criddle (1950) developed a method for estimating consumptive use for irrigation scheduling: This method was developed by correlating measured consumptive use data of individual crops with monthly temperature, monthly percentage of yearly daytime hours, precipitation, and growing season. This empirical formula is based on measurements of crop use in semi-arid areas of Texas and New Mexico. Although this method has been proven to yield accurate results in the warm semi-arid areas of the United States poor results have been obtained elsewhere. Laycock (1967) suggested that the Blaney and Criddle formula overestimates "potential consumptive use", (i.e. similar to Thornthwaite's concept of potential evapotranspiration), in southern Canada and grossly overestimates potential consumptive use in northern Canada. The overestimation is due to the fact that the Blaney and Criddle formula makes fairly large allowances for increased daylength. Thus, in northern latitudes where daylength increases rapidly in summer with only slight increases in latitude the formula greatly overestimates potential consumptive use.

Lowry and Johnson devised a method for estimating consumptive use for

agriculture based on a linear relationship "effective heat" (i.e. accumulation, in day-degrees, of maximum daily growing season temperature above 0° centigrade.), and comsumptive use (Criddle, 1945). One problem with the Lowry and Johnson formula is determining the start of the growing season or what might be considered potential evapotranspiration. Effectively the growing season starts with a floating 5 day mean minimum temperature over 0° centigrade but in the study area there may be large departures from what might be considered the growing season: Laycock (1967) found that in the prairies values obtained by the Lowry and Johnson consumptive use method are similar to values derived by the Thornthwaite method. Both the Blaney and Criddle and Lowry and Johnson formulas could be adapted for use in the study area but neither has a very effective employment of soil moisture data in an annual budget of use for water balance calculations. It seems desirable to employ the Thornthwaite procedure which does include water balance calculations.

There are many other researchers world wide working on both analytical and empirical formulas to estimate potential evapotranspiration. Budyko (1956), a Russian Scientist has developed an equation based on the energy balance theory. Highly technical solar radiation and meteorological data are required for Budyko's equation which are not available from any stations near the study area.

Many other references such as Chow (1964), Gray (1970), Ward (1967), Penman (1948), and Chang (1974) provide an excellent review of all of the methods for estimating potential evapotranspiration previously discussed as well as discussion of many less well known methods which have

not been included in this thesis.

4.6 Water Balance Equation Inputs

The water balance approach adopted by Thornthwaite has a wide range of possible applications (see section 4.3). Many of the objectives of the study are based on a knowledge of surplus and deficit patterns as determined using water balance approach. One of the more general objectives is to gain knowledge of the regional yearly yield and regime patterns in the study area. To provide these patterns the water balance is utilized but certain input data are essential. The relationship of climatic factors, which are the input data, are presented in the water balance equation as:

Precipitation = (Potential Evapotranspiration - Deficit) + Surplus ± Storage Change, with terms defined as:

Precipitation: any water, either liquid or solid, which has fallen on the earth's surface.

Potential Evapotranspiration: the amount of water vapor released to the atmosphere by means of evaporation from soil and water bodies plus transpiration from vegetation provided soil moisture is never limiting.

Deficit: the difference between potential evapotranspiration and actual evapotranspiration (i.e. the moisture that was actually lost to the atmosphere via evaporation and transpiration).

Surplus: the amount of incoming precipitation that exceeds the potential evapotranspiration after soil has reached field capacity. This is approximately equal to surface plus ground water flow.

Storage Change: is the result of an increase or decrease of moisture held within the root zone of the soil during the time period under consideration.

The input data needed are monthly and daily meteorological data of precipitation as well as monthly and daily temperature data and the latitude of the study area. Input data on the soil moisture storage capacity and amount held in storage at the beginning of computation are also required. If these data are available the deficits and surpluses can be computed by bookkeeping procedures. Although not a direct input, stream flow data can be used to determine the relationship between precipitation and as a check on the reliability of estimated surplus.

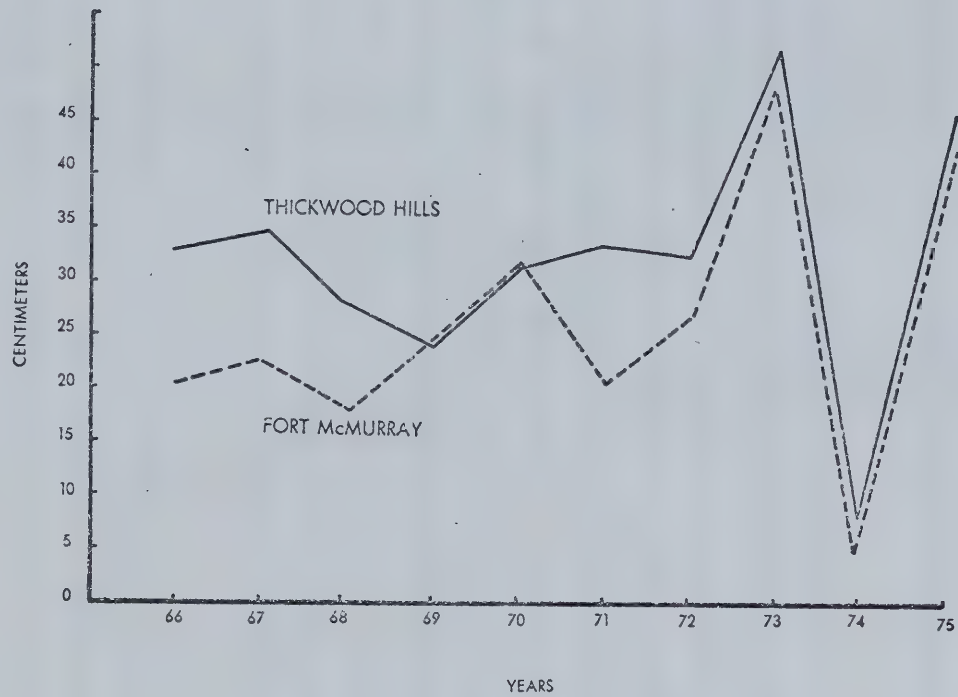
Precipitation data were available from three meteorological stations in or near the study area (Figure 1.2). Precipitation and temperature data from Fort McMurray were used to compute a monthly balance from 1945 to 1977. Meteorological data from Fort McMurray are the longest and most extensive records collected in north-eastern Alberta. For comparative purposes monthly and daily water balances were computed using meteorological data recorded at Mildred Lake Site which is located adjacent to the construction site. Operation of this meteorological station began during the summer of 1973 with the site being located in the mining area. During the summer of 1974 the site was moved to a new location adjacent to the construction area. Conditions around the site have been changing continually since installation. Seasonal precipitation and temperature from Thickwood Hills Lookout (LO), collected by employees of Alberta Forest Service, were used as an indicator of the different climatic patterns in the headwater areas of Beaver Creek.[1] Many other meteorological stations

[1]Temperature and precipitation data are available from May to September and often there are missing data during this period.

Figure 4.1

TOTAL PRECIPITATION MAY TO SEPTEMBER

(FORT McMURRAY and THICKWOOD HILLS)



in north-eastern Alberta provide data which enabled the author to verify weather patterns at the three locations previously mentioned and develop a broader regional perspective. Although meteorological data are recorded at only two specific sites within the basin, the general precipitation patterns are thought to be reasonably accurate for the purposes of this study.

Under-catch in precipitation measurements and increased precipitation due to an orographic effect are two major problems affecting the water balance. The greatest measurement error in gauging precipitation is caused by wind providing upward acceleration over the gauge. Reliable evaluation of errors caused by the wind are difficult to estimate because the true precipitation is equally hard to determine. After an exhaustive review of the literature Bruce and Clark (1966) suggest that undercatch in rainfall may be as high as 15 percent. Gray (1970) presented a table showing a deficiency in snow catch of 47 percent with a wind speed of 7 meters per second. Adjustments for increased rainfall due to the orographic effect with adjustments in the water balance are included in section 4.6.

Potential evapotranspiration is the most difficult input parameter to estimate in the water balance equation. Many methods have been devised which measure potential evapotranspiration in small test plots under a given set of field conditions. Weighing lysimeters of high sensitivity can provide an accurate estimate of potential evapotranspiration if correctly installed and maintained. No tool capable of measuring potential evapotranspiration has been developed which can be easily transported

into the field. Lack of an analytic tool or method for measuring potential evapotranspiration caused many researchers to develop and depend on empirical relationships to estimate potential evapotranspiration (i.e. similar to concepts of potential transpiration or comsumptive use). The author wants to stress that the Thornthwaite relationship is empirical and was developed in a climate regime typified by central and eastern North America. None of these techniques, including Thornthwaite's, should be used outside the area they were developed in without first testing them. Only after an empirical method is adjusted or modified can more specific (i.e. daily or weekly) patterns of potential evapotranspiration be examined.

The Thornthwaite method (1948) for estimating potential evapotranspiration is used as an input for water balance calculations while the Penman method (1948) is used as a crosscheck. Thornthwaite's formula (1948) for estimating potential evapotranspiration with simplification by Hare in the late 1950's is presented as:

$$E = 1.6\ (10\ T/I)^{a}$$

(E) is unadjusted potential evapotranspiration computed on the basis of a 30 day month, each with twelve hours of daylight, (T) is the mean monthly temperature in centigrade, (a) is a constant which changes with location, and (I) is the yearly heat index. A correction factor was used to adjust for daylength and season, for latitudes to 50° N and S. In estimating potential evapotranspiration for the study area the 50° N latitude correction factor was applied. Although the study area has a greater daylength then 50° N latitude, potential evapotranspiration estimates are not underestimated for the study area. Laycock (1967)

found that the 50° N correction could be used in areas farther north for two reasons: first, frosts in spring and fall reduce potential evapotranspiration by approximately as much as extra daylength added to it; second, an increasing proportion of solar insolation is used for melting ice, snow, and frozen ground with increasing northerly latitude. Therefore, a compromise is reached whereby the 50° N correction factor also applies to areas further north.

Penman (1948) combined the energy balance an aerodynamic approaches used to measure potential evapotranspiration into a theoretically sound equation where:

$$E = (^{\Delta}/\gamma\ H + E\alpha)\ /\ (^{\Delta}/\gamma + X).$$

The equation is used to estimate hypothetical evaporation from an open water surface and then an empirical coefficient is used to convert the results to potential evapotranspiration.

As mentioned earlier, data aquisition for computation of the Penman method (for estimating potential evapotranspiration) is often difficult. In this study it was necessary to use temperature and wind data collected at Fort McMurray until July, 1973 when data from Mildred Lake became available. Solar radiation data received at Stony Plain, Alberta were used in the Penman equation, as it is the closest receiving station to the study area. Computation of the equation was done on the computer facilities at the University of Alberta. The program was taken from Verma (1968) but much revision was done by the author as Verma's program would not run as presented. The computer program used is presented and

explained in Apppendix 1.

Monthly values of potential evapotranspiration were calculated using both the Thornthwaite and Penman methods, with six years of data, 1970 to 1975, presented in table 4.1. Potential evapotranspiration

Table 4.1: Potential Evapotranspiration

Thornthwaite Versus Penman (Cm)*

Year	Month	Thornthwaite (Cm)	Penman (Cm)
1975	May	8.1	8.8
	June	10.4	9.4
	July	13.6	10.7
	August	9.5	6.5
	September	6.5	4.6
	Season Total	48.1	40.0
1974	May	6.0	7.0
	June	11.4	11.3
	July	11.5	10.2
	August	9.5	6.6
	September	4.9	2.6
	Season Total	43.3	37.7

Table 4.1 Continuation

Year	Month	Thornthwaite (Cm)	Penman (Cm)
1973	May	9.1	8.6
	June	11.4	11.0
	July	12.5	10.8
	August	10.5	7.0
	September	5.7	3.3
	Season Total	49.2	40.7
1972	May	9.1	7.9
	June	11.4	9.0
	July	10.4	8.5
	August	11.4	8.5
	September	3.2	3.0
	Season Total	45.5	36.9
1971	May	9.1	8.7
	June	11.4	7.3
	July	11.4	9.0
	August	12.4	10.4
	September	5.6	4.6
	Season Total	49.9	40.0

Table 4.1 Continuation

Year	Month	Thornthwaite (Cm)	Penman (Cm)
1970	May	7.1	7.4
	June	12.4	9.4
	July	12.5	8.7
	August	10.5	6.8
	September	5.6	2.9
	Season Total	48.1	35.2
Six Year Averages	May	8.1	8.0
	June	11.4	9.6
	July	12.0	9.7
	August	10.6	7.6
	September	6.2	3.5
	Season Total	48.3	38.4

* Estimates of potential evapotranspiration are based on a seasonal basis from May through September. Thornthwaite estimates are based on daily temperature and precipitation data.

is computed only for the months May through September because mean monthly temperature is near or below 0° centigrade in all other months causing potential evapotranspiration to be nil (Verma, 1968). In all but two months shown, calculated potential evapotranspiration is less using the Penman method compared to Thornthwaite's method. In their

work Sanderson and Phillips (1967) and Laycock (1967) have shown that it is highly unlikely for potential evapotranspiration to be as low as the 6.5 centimeter estimate for August, 1975. In 1975 mean monthly temperature in August was 6° centigrade greater than in May of the same year yet potential evapotranspiration is 2.3 centimeters greater in May using the Penman method. A comparison of potential evapotranspiration for the same months using the Thornthwaite method shows that although potential evapotranspiration is relatively low it is still 1.1 centimeters greater in August than in May, In fact potential evapotranspiration, using the Penman method, is lower in August than in May in four out of six years under study.

The Penman method has been proven to work quite well in Marine West Coast climates including Southern England where the equation was first tested (Penman, 1948). Solar insolation is the dominating variable while mean monthly air temperature is subordinate in the equation. Thus in areas of Marine West Coast climates solar insolation would be the dominant factor as gradual changes in temperature would occur from one season to the next and large daily fluctuations in air temperature would not occur. Thus, a major water body greatly affects mean air temperature.

An adjusted estimate of potential evapotranspiration was made to determine the importance of solar insolation versus mean monthly temperature with the results presented in table 4.2. Increasing mean daily solar insolation from 413 langleys[1] per day to 500 langleys per day

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[1]A langley is equal to one gram calorie per square centimeter (Strahler, 1975).

Table 4.2: Adjusted Penman Potential

Evapotranspiration Values (Cm)

Year	Month	Mean Monthly Temperature	Thornthwaite	Penman	Adjusted Penman
1975	August	9.6° C	9.2	6.5	8.7
1974	August	13° → 17.2° C	9.5	6.7	7.5

resulted in an additional 2.2 centimeters of potential evapotranspiration in August, 1975 with no increase in mean monthly temperature. At the same time increasing mean monthly temperature by 4.2° centigrade from 13° centigrade to 17.2° centigrade in August 1974 provided only an additional 1.2 centimeters of potential evaptranspiration for the month. Other adjustments of variables in the equation were made but none provided a major increase in estimates of potential evapotranspiration (i.e. changes were made in wind speed, percent possible sunshine, and relative humidity).

Yearly estimates of potential evapotranspiration using both the Penman and Thornthwaite methods are presented in table 4.3. Potential evapotranspiration is greater in all years using Thornthwaite's method with a range anywhere from 5.6 centimeters to 13.2 centimeters difference.[1] Potential evapotranspiration estimates would be lower using the Penman method even if nominal allowances were made for April and October.

[1]These differences are using seasonal potential evapotranspiration data in table 4.3

Table 4.3: Yearly Potential Evapotranspiration Rates

Penman and Thornthwaite (Cm)*

Year	Thornthwaite (Yearly)	Thornthwaite (Seasonal)	Penman
1975	51.9	48.0	40.0
1974	48.8	43.3	37.7
1973	53.9	50.2	40.7
1972	46.3	45.6	37.0
1971	55.7	50.0	40.0
1970	52.4	48.2	35.0

* Thornthwaite yearly estimates are based on daily computations over a 12 month period while the seasonal estimates are based on the five month period May to September.

If yearly totals of potential evapotranspiration were as low as shown by the Penman estimates (table 4.3) surpluses would be much greater than runoff discharge indicates (further discussion of runoff patterns is included in sections 5.3). If Penman's estimates of potential evapotranspiration were used a coefficient of 1.2 would be necessary to increase the estimates to values similar to Thornthwaite estimates.

Along with measurements of precipitation and estimates of potential evapotranspiration one must determine the soil moisture capacity levels before developing the water balance equation. Original storage capacity levels were based on work done by researchers of the Laboratory of Climatology near Seabrook, New Jersey. Thornthwaite and Mather (1955,

p.23) stated:

> The moisture holding capacity of a soil depends on the depth of the soil layer considered, and the type and structure of the soil. It can vary from just a few millimeters on a shallow sand to well over 40 centimeters on a deep well-aerated silt loam. The roots of plants compensate somewhat for the variable nature of soil for on sandy soils plants will be deep-rooted while on silts and clay the plants tend to be more shallow-rooted. Thus, the depth of water available to the roots of mature plants is not as variable as might be thought, at first. Of course, young plants or mature trees will have root systems which ramify through a markedly different depth of soil and so they will have available to them quite different amounts of moisture.

Thornthwaite and Mather (1957) concluded that soil moisture storage capacity levels could be as high as 40 centimeters for a closed mature forest in a clay soil. Closer to the study area Laycock (1967) and MacIver (1966) have suggested that no area in Alberta would have that high a useable soil moisture storage capacity. In their work storage capacities in centimeters were assigned to various surficial covers as follows:

1) 1.3 (.5") - cleared areas of packed soil, roads, and rooftops within the construction site.
2) 5 (2") - cleared areas with limited regrowth of vegetation, cleared areas in the construction area, marsh, and muskeg areas.
3) 10 (4") - sparsely treed or bushy muskeg areas or Jackpine stands growing on sandy soil.
4) 15 (6") - immature decidious cover or previously burned area.
5) 25 (10") - mature closed crown forest with a well developed soil and good drainage.
6) Surface water-storage capacity is considered unlimited and when estimating potential evapotranspiration add one-half the

deficit (prevailing in the surrounding region) from the 15 centimeter storage to allow for advected heat. Using the 15 centimeter storage capacity for calculation of additional potential evapotranspiration is a regional calculation and changes are possible. Surface water potential evapotranspiration estimates would also apply to phreatophytes growing in the lowland areas.

Two long-term water balance equations for different locations within the Fort McMurray region are presented as follows:

Table 4.4: Water Balance Equations - Fort McMurray and Stony Mountain

Long Term Water Balance Equation (Cm)

Fort McMurray A[1]	44.7 = (50.2 - 11.4) + 5.9*
Stony Mountain LO[2]	63.6 = (43.2 - 2.5) +22.9*

* Soil moisture storage was assumed to be 10 centimeters

The long term water balance equation for Fort McMurray is representative of river basins which drain the table lands above the escarpment along the Athabasca River. Meteorological data collected at Fort McMurray provides the longest period of recorded data available in north-eastern Alberta.

[1] Long term water balance was computed on a daily basis from 1945 through 1975.

[2] Water balance equation for Stony Mountain was taken from Hallock (1976).

Until recently most meteorological data collected in north-eastern Alberta were received from settlements within the Athabasca River Valley and included Fort McMurray, Fort Chipewyan and Fort Smith. The water balance equation for Stony Mountain Lookout was developed by Hallock (1976) to provide an equation representative of the upland areas within Gregoire Lake Basin and to demonstrate the great variation in water balance patterns within the region. The great difference in surplus and deficiency is provided by the change in elevation; Fort McMurray is located at 369 meters above sea level (MASL) while Stony Mountain Lookout is at an altitude of 762 MASL. This change in elevation affects both precipitation type and amount, and potential evapotranspiration.

The water balance equation presented for Fort McMurray is representative of the lower reaches of the study area, as precipitation and temperature data between Fort McMurray and Mildred Lake are similar. No major anomalies were evident with only three full years of meteorological data available from Mildred Lake. The only major deviations noted in weather patterns between the two sites have occurred in the summer when heavy precipitation of convectional origin has been recorded at one site and not the other. In this study the author has made the assumption that this convectional precipitation will average out at the two sites in question over a longer time period.

Although the long term water balance equation is representative of the patterns in the lower reaches of Beaver Creek Basin it does not serve as an accurate indicator of water balance patterns in the headwater regions of the study area. Before any estimation of regime and yield

patterns can be determined the water balance equation must be adjusted for the upland areas. With an increase in elevation in the Thickwood Hills there is a microclimatic change which provides a decrease in temperature and also an increase in precipitation caused by orgraphic uplifting of air. Hallock (1976) found that potential evapotranspiration is nearly 6 centimeters lower on the Stony Mountain Pleateau than potential evapotranspiration estimates made using Fort McMurray data. Hallock also found that precipitation is approximately 64 centimeters per year on the Stony Mountain Plateau or nearly 20 centimeters greater than the precipitation recorded at Fort McMurray. Due to the fact that only a small percentage of the total precipitation leaves the study area as surface runoff from lowland areas, adjustments such as these can provide striking increases in surpluses with consequent decreases in deficiencies.

For the Thickwood Hills a reasonably accurate adjustment of potential evapotranspiration can be made if a vertical lapse rate of .6° centigrade per 100 meters is used. Using this vertical lapse rate, mean monthly temperatures in the headwater regions of Beaver Creek would be 1.2° centigrade cooler than those recorded at Fort McMurray. Examination of scattered mean monthly temperature data has shown that temperatures are consistently between 1° and 2° centigrade cooler at the Thickwood Hills Lookout than at Fort McMurray. Temperature data from Thickwood Hills Lookout were not available for the months, October to April, but this is not thought to be a problem because potential evapotranspiration is assumed to be nil during the months of November to March, inclusive (i.e. whenever mean monthly temperature is less than 0° centigrade).

Potential evapotranspiration during April and October at Fort McMurray is 1.7 centimeters and 1.4 centimeters respectively and these estimates are almost zero after an adjustment in temperature is made for the Thickwood Hills Lookout. Yearly potential evapotranspiration is 3 to 4 centimeters less in the headwater regions of Beaver Creek Basin than that in the lower parts of the study area.

Precipitation, due to orographic influence, is greater in the headwater regions of Beaver Creek than that recorded at either Fort McMurray or Mildred Lake. Adjustment of precipitation as an input for the water balance equation is very difficult because of the variability from year to year. In figure 4.1 the seasonal precipitation recorded at Thickwood Hills Lookout is compared to that recorded at Fort McMurray for the months available. In most years summer precipitation is lower at Fort McMurray than at Thickwood Hills Lookout. Using summer precipitation data for the period 1964 to 1975 precipitation averaged 20 percent greater at Thickwood Hills Lookout.

Hallock (1976) found that there was an orographic effect on snowpack accumulation directly related to the Stony Mountain Escarpment. He had data from only one field season so no estimates of increase in winter precipitation were made. No data from the Thickwood Hills have been gathered until this past winter. A field trip to the study area in March was planned to make visual observations and take snow depth measurements in the Thickwood Hills and near the Construction site. This field trip was cancelled because of the light snow accumulations and the early ripening of snow. The author felt that data collected would not have

been representative of the snowpack patterns in the study area in most years. Yearly precipitation at Thickwood Hills for water balance procedures, was increased by roughly 15 percent relative to Fort McMurray.

An adjusted water balance equation, representative of the headwater areas of Beaver Creek, is presented as follows:

Table 4.5: Water Balance Equation - Thickwood Hills

Water Balance Adjusted for Precipitation and Potential Evapotranspiration

$$51.4 = (46.2 - 11.4) + 16.6$$

This water balance equation is only representative of areas closest to Thickwood Hills Lookout. Therefore, water balance patterns in Beaver Creek Basin vary from the equation in table 4.5, representative of the uplands, to the water balance equation presented in table 4.4 which is representative of the lower reaches of the study area. In all of the water balance equations presented thus far, a 10 centimeter soil moisture capacity has been used. In chapter five water balance patterns for the full range of soil moisture storage levels are presented.

CHAPTER V

Water Balance Patterns

5.1 Introduction

In this chapter, the water balance patterns of the Beaver Creek Basin are discussed. In section 5.2 the emphasis is upon defining the over-all water balance in the study area, especially the patterns which have prevailed in the 1970's. In section 5.3 basin yield data are presented for the period 1972 through 1976 with a discussion of these yield patterns. Estimated yield is compared to the gauged yield in tables 5.7 to 5.11. Variations in yield is discussed in section 5.4 with a review of Kellerhals (1973) study. A comparison of daily versus monthly surplus and deficiency patterns is included in the final section 5.5, along with an explanation of the differences which are inherent using each procedure.

5.2 Over-All Water Balance Patterns

Many different procedures have been developed for calculating the water balance and the various input data, which have been discussed in previous sections (i.e. potential evapotranspiration, soil moisture storage, surface and ground water flow, and precipitation), (Laycock, 1976). In this study, water balance procedures adopted by Thornthwaite 1948, 1955, and 1957 as well as Thornthwaite's method for estimating potential evapotranspiration are used in analysing water balance patterns

in the study area. Water held as soil moisture is not equally available to the plant, from field capacity to the wilting point. Some deficit occurs as soon as the soil moisture drops below field capacity and the water needs of vegetation become more difficult to meet. (Thornthwaite Associates, 1964). Thornthwaite (1948) presented a soil moisture relationship whereby moisture held in storage and moisture available to plants were proportional (e.g., if soil moisture storage capacity was half the maximum amount, evapotranspiration would be half the potential evapotranspiration under optimal meteorological conditions). This is one procedural phase that has not been used, for the simple reason that a modulated water balance would be too time consuming for the doubtful improvement in results. In using the water balance procedure for this study it was assumed that all moisture left in storage at the end of the month was readily available for potential evapotranspiration in the following month. Given these conditions using long term normal data for Fort McMurray Airport an equation is derived as follows:

$$44.7 = (50.2 - 11.4) + 5.9,$$

where the soil moisture storage capacity is 10 centimeters. This long term pattern is presented graphically in figure 5.1. This long term pattern can be compared to the patterns presented in figures 5.2 to 5.7 representative of the years 1971 to 1976,(graphs are based on data shown in Tables 5.1 - 5.6). In the long term water balance water recharge normally takes place in the early months of the year. This recharge period begins in late October and lasts until late March, with most of the precipitation falling as snow. This recharge period is highly vari-

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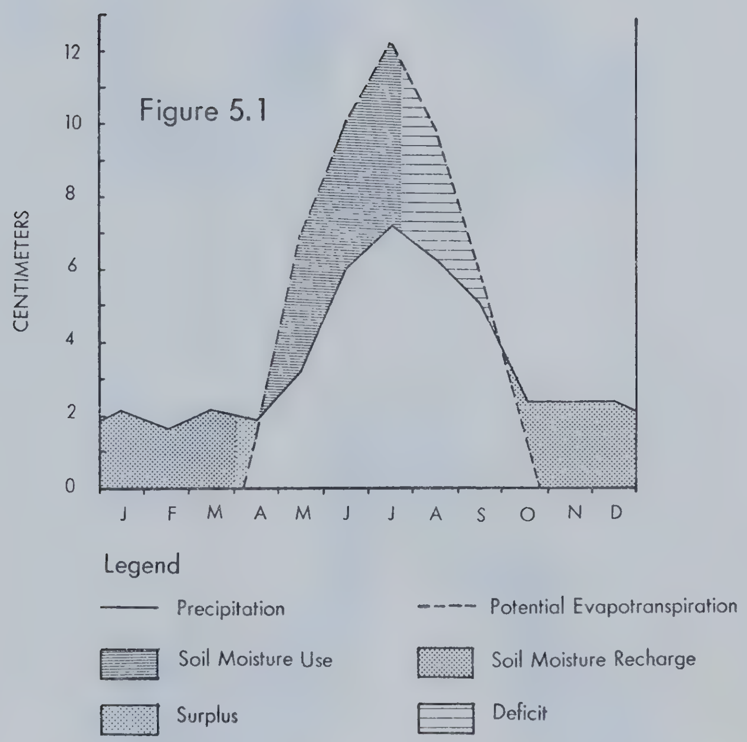
WATER BALANCE DIAGRAM

Long Term Normal



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WATER BALANCE DIAGRAM

10 Centimeter Storage

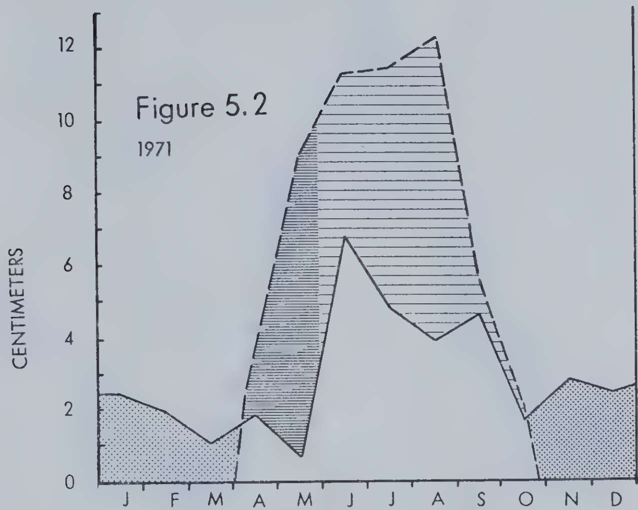

Figure 5.2

1971

35 = (54 − 21) + 6 − 4

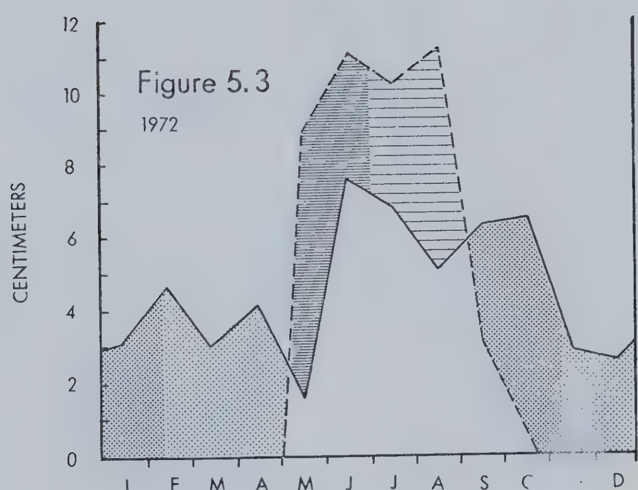

Figure 5.3

1972

57 = (46 − 11) + 17 + 5

Legend

- Precipitation
- Potential Evapotranspiration
- Soil Moisture Use
- Soil Moisture Recharge
- Surplus
- Deficit

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WATER BALANCE DIAGRAM

10 Centimeter Storage

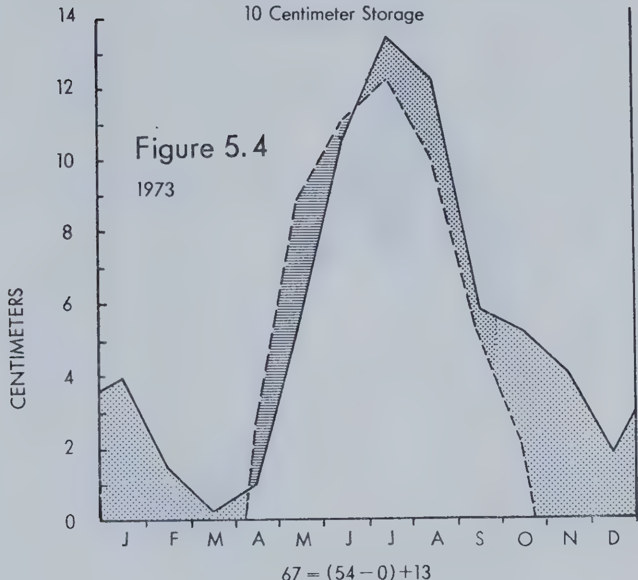

Figure 5.4
1973

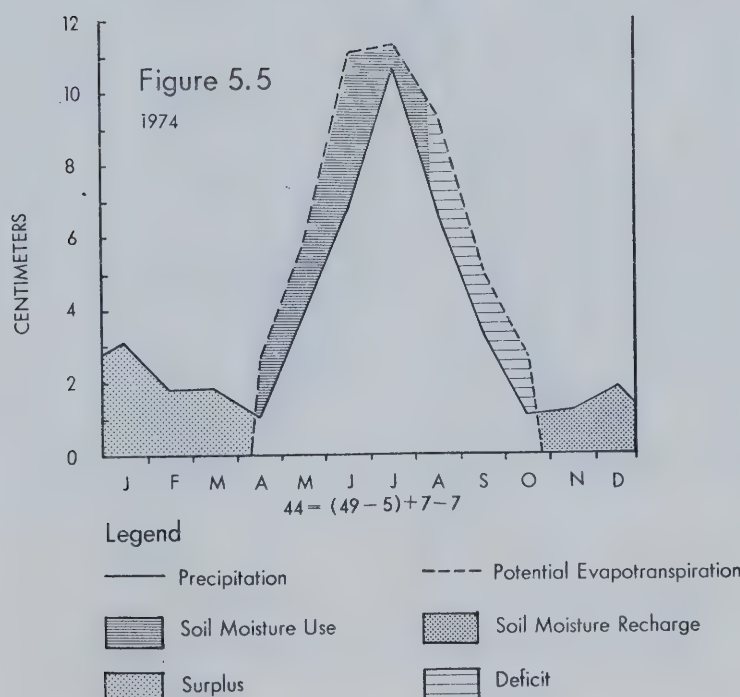

Figure 5.5
1974

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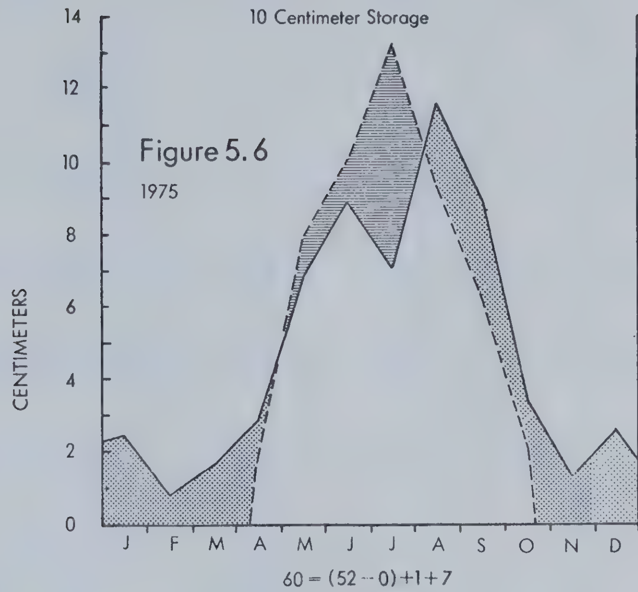
WATER BALANCE DIAGRAM



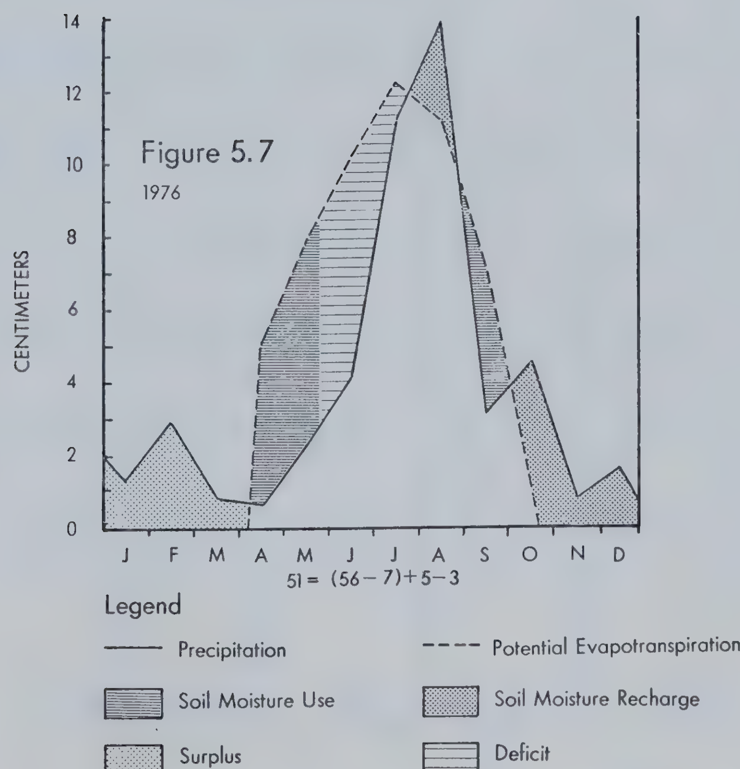


Table 5.1: Monthly Water Balance - 1971 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-26	-12.6	-8.4	4.3	12.2	15.3	15.8	17.6	8.8	3.6	-9.2	-21.2	
	PE	-	-	-	3.3	8.8	11.1	11.5	11.5	5.2	2.3	-	-	54.1
	Ppt.	2.3	1.8	1.0	1.9	0.7	6.8	4.8	3.8	4.4	1.7	2.9	2.5	35.1
	S.C.	2.3	1.8	1.0	-1.3	-8.1	-4.2	-6.7	-7.7	-0.7	-0.6	2.9	2.5	
1.3	St.	1.3	1.3	1.3	-	-	1.0	-	-	0.7	0.7	1.3	1.3	
3.5	Surp.	2.3	1.8	0.9	1.4	-	1.3	0.2	-	0.4	-	2.3	2.5	13.6
	Def.	-	-	-	1.5	8.1	6.6	5.9	7.7	1.9	0.6	-	-	32.6
5.0	St.	5.0	5.0	5.0	2.2	-	2.4	-	-	0.7	0.6	3.6	5.0	
2.6	Surp.	2.3	1.8	0.9	1.4	-	-	-	-	-	-	-	1.0	7.6
	Def.	-	-	-	-	5.8	6.6	4.3	7.7	1.4	0.6	-	-	26.7
10.0	St.	10.0	10.0	10.0	7.3	-	2.4	-	-	0.7	0.6	3.6	6.1	
1.1	Surp.	2.3	1.8	0.9	1.4	-	-	-	-	-	-	-	-	6.6
	Def.	-	-	-	-	0.8	6.6	4.3	7.7	1.4	0.6	-	-	21.6
15.0	St.	15.0	15.0	15.0	12.4	4.2	2.4	-	-	0.7	0.6	3.6	6.1	
13.6	Surp.	0.7	1.8	0.9	1.4	-	-	-	-	-	-	-	-	5.0
	Def.	-	-	-	-	-	2.4	4.3	7.7	1.4	0.6	-	-	16.5
25.0	St.	24.7	25.0	25.0	22.5	14.4	10.1	3.4	-	0.7	0.7	3.6	6.1	
22.4	Surp.	-	1.2	0.9	1.4	-	-	-	-	-	-	-	-	3.6
	Def.	-	-	-	-	-	-	-	4.2	1.4	0.6	-	-	6.4

* Environment Canada, Monthly Meteorological Summaries, 1971.

Table 5.2: Monthly Water Balance - 1972 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-26.0	-22.1	-7.1	-0.6	11.9	15.2	14.2	16.7	3.7	0.2	-8.1	-21.3	
	PE	-	-	.45	1.6	9.0	11.3	10.9	11.4	2.7	1.3	0.5	-	48.7
	Ppt.	3.2	4.7	3.0	4.2	1.6	7.5	7.0	5.3	6.5	6.6	4.2	2.6	56.4
	S.C.	3.2	4.7	2.55	1.6	-7.4	-3.8	-3.9	-5.9	3.8	5.3	3.7	2.6	
1.2	St.	1.2	1.2	1.2	1.2	0.1	0.1	0.4	-	-	1.2	1.2	1.2	
4.8	Surp.	3.2	4.7	2.5	2.6	-	1.0	0.9	0.5	3.6	5.3	4.2	2.6	31.1
	Def.	-	-	-	-	7.3	5.0	4.4	6.6	1.0	-	-	-	24.3
5.0	St.	5.0	5.0	5.0	5.0	3.9	0.4	-	-	4.8	5.0	5.0	5.0	
1.0	Surp.	3.2	4.7	2.6	3.6	-	-	-	-	-	-	-	-	26.3
	Def.	-	-	-	-	3.5	3.9	3.5	6.0	1.0	-	-	-	18.2
10.0	St.	9.3	10.0	10.0	9.0	1.6	0.4	-	-	4.8	5.0	5.0	5.0	
6.1	Surp.	-	3.9	2.6	3.6	-	-	-	-	-	-	-	-	17.2
	Def.	-	-	-	-	-	2.4	3.5	6.0	1.0	-	-	-	13.2
15.0	St.	9.3	14.1	15.1	14.1	6.7	2.9	-	-	4.8	10.1	14.4	15.0	
6.1	Surp.	-	-	0.7	3.6	-	-	-	-	-	-	-	1.8	6.1
	Def.	-	-	-	-	-	-	.96	6.0	1.0	-	-	-	8.1
25.0	St.	9.3	14.1	16.7	19.3	11.9	8.2	4.2	-	4.8	10.1	14.4	17.0	
6.1	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	0.0
	Def.	-	-	-	-	-	-	-	1.8	1.0	-	-	-	2.8

* Environment Canada, Monthly Meteorological Summaries, 1972.

Table 5.3: Monthly Water Balance - 1973 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-16.3	-14.9	-2.8	3.0	12.8	14.5	17.0	15.0	9.6	3.3	-14.0	-19.5	
	PE	-	-	0.4	2.9	9.3	10.3	12.4	10.0	5.5	2.1	-	-	53.5
	Ppt.	4.3	1.6	0.4	1.1	5.6	10.7	13.7	12.4	5.8	5.4	4.2	1.9	67.4
	S.C.	4.3	1.6	-	-1.7	-3.7	0.4	1.4	2.4	0.3	3.3	4.2	1.9	
1.3	St.	1.3	1.3	-	1.3	-	-	0.3	1.3	1.3	1.3	1.3	-	
6.9	Surp.	4.3	1.4	0.3	-	0.9	4.0	5.1	5.6	1.6	3.2	4.2	1.9	33.0
	Def.	-	-	-	0.9	5.9	2.4	3.9	3.7	2.1	-	-	-	19.1
5.0	St.	5.0	5.0	4.6	2.8	2.2	1.3	1.0	1.5	2.8	5.0	5.0	5.0	
6.9	Surp.	4.3	1.4	0.3	-	-	1.2	1.4	1.8	-	1.0	4.2	1.9	17.9
	Def.	-	-	-	-	3.0	-	-	-	0.9	-	-	-	3.9
10.0	St.	10.0	10.0	9.7	7.9	4.2	4.6	5.8	6.6	6.9	10.0	10.0	10.0	
6.9	Surp.	4.3	1.4	0.3	-	-	-	-	1.5	-	0.1	4.2	1.9	13.9
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	-
15.0	St.	15.0	15.0	14.8	13.0	9.3	9.7	10.9	11.7	12.0	15.0	15.0	15.0	
1.8	Surp.	4.3	1.4	0.3	-	-	-	-	1.5	-	0.1	4.2	1.9	13.9
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	-
25.0	St.	17.0	21.3	22.8	21.0	17.3	17.7	18.9	21.2	21.5	24.8	25.0	25.0	
17.0	Surp.	-	-	-	-	-	-	-	-	-	-	3.6	1.9	5.6
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	-

* Environment Canada, Monthly Meteorological Summaries, 1973.

Table 5.4: Monthly Water Balance - 1974 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-24.5	-14.9	-14.0	3.4	7.2	14.9	15.7	13.0	7.6	4.2	-4.5	-9.3	
	PE	-	-	-	3.4	6.2	11.0	11.7	9.2	4.9	2.6	0.5	-	49.9
	Ppt.	3.2	1.8	1.8	1.2	3.8	7.1	10.8	6.7	3.3	1.1	1.2	1.8	
	S.C.	3.2	1.8	1.8	-2.2	-2.3	-3.0	-0.9	-2.5	-1.5	-1.4	0.7	1.8	
1.3	St.	1.3	1.3	1.3	-	0.6	0.3	1.3	0.9	1.3	0.2	1.3	1.3	
6.1	Surp.	3.2	1.8	1.8	0.8	0.1	0.3	1.3	1.4	0.2	-	-	1.8	13.0
	Def.	-	-	-	1.8	3.1	3.9	3.1	3.7	2.1	0.4	0.3	0.3	18.6
5.0	St.	5.0	5.0	5.0	1.9	0.6	0.3	1.7	2.4	1.4	0.2	1.3	3.1	
6.1	Surp.	3.2	1.8	1.8	0.8	-	-	-	-	-	-	-	-	7.6
	Def.	-	-	-	-	1.0	3.6	2.2	3.2	0.6	0.1	0.3	-	11.3
10.0	St.	10.0	10.0	10.0	7.0	4.6	0.7	1.7	2.4	1.4	0.2	1.3	3.1	
6.1	Surp.	3.2	1.8	1.8	0.8	-	-	-	-	-	-	-	-	7.6
	Def.	-	-	-	-	-	-	1.8	3.2	0.6	0.1	1.3	-	6.2
15.0	St.	15.0	15.0	15.0	12.1	9.7	5.8	4.9	2.4	1.4	0.2	1.3	3.1	
6.1	Surp.	3.2	1.8	1.8	0.8	-	-	-	-	-	-	-	-	7.6
	Def.	-	-	-	-	-	-	-	-	0.6	0.1	0.3	-	1.1
25.0	St.	25.0	25.0	25.0	22.3	19.9	16.0	15.0	12.5	10.9	9.4	10.2	12.1	
5.6	Surp.	3.2	1.8	1.8	0.8	-	-	-	-	-	-	-	-	7.6
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	-

* Environment Canada, Monthly Meteorological Summaries, 1974.

Table 5.5: Monthly Water Balance - 1975 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-19.2	-16.4	-9.6	1.7	9.6	13.9	18.0	13.0	10.0	3.1	-8.3	-18.9	
	PE	-	0.1	-	2.8	7.6	10.4	13.3	9.2	6.0	2.3	0.1	-	52.2
	Ppt.	2.54	0.7	1.6	2.8	7.0	9.0	7.1	11.9	9.0	3.5	1.3	2.4	59.4
	S.C.	2.54	0.6	1.6	-	-0.6	-1.4	-6.1	2.6	2.9	1.1	1.3	2.4	
1.3	St.	1.3	1.1	1.3	1.3	-	0.8	0.1	1.1	1.0	1.0	1.3	1.3	
1.8	Surp.	0.5	0.7	1.5	0.4	1.7	0.7	1.9	3.6	4.1	1.1	1.1	2.4	22.0
	Def.	-	-	-	0.3	1.1	3.0	7.3	1.9	1.0	-	-	-	14.8
5.0	St.	5.0	4.9	5.0	5.0	3.7	2.3	0.1	4.7	4.4	4.8	5.0	5.0	
1.8	Surp.	0.5	0.7	1.5	0.4	0.6	-	-	-	3.3	0.7	1.0	2.4	11.5
	Def.	-	-	-	0.3	-	-	3.9	1.9	-	-	-	-	6.2
10.0	St.	5.6	6.2	7.9	7.9	7.3	5.9	0.1	4.7	7.7	8.9	10.0	10.1	
3.1	Surp.	-	-	-	-	-	-	-	-	-	-	-	2.4	2.4
	Def.	-	-	-	-	-	-	0.4	1.9	-	-	-	-	2.3
15.0	St.	5.6	6.2	7.9	7.9	7.3	5.9	0.1	4.7	7.7	8.9	10.2	12.6	
3.1	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	-	0.4	1.9					2.3
25.0	St.	14.6	15.3	16.8	16.9	16.3	14.9	8.7	11.4	14.4	15.5	16.8	19.2	
12.1	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

* Environment Canada, Monthly Meteorological Summaries, 1975.

Table 5.6: Monthly Water Balance - 1976 - Based on a Summary of Daily Data.*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-16.6	-14.9	-8.5	7.1	11.5	14.2	16.5	16.3	12.1	1.8	-4.9	-17.0	
	PE	-	-	0.3	4.8	8.8	10.8	12.4	11.1	7.5	1.8	0.3	-	58.2
	Ppt.	1.3	2.9	0.8	0.6	2.2	4.0	11.4	17.3	3.1	4.5	0.8	1.6	51.2
	S.C.	1.3	2.9	0.5	-4.1	-6.5	-6.5	-0.9	6.1	-4.3	2.7	0.5	1.6	
1.3	St.	1.3	1.3	0.9	-	-	-	-	1.3	-	1.3	1.3	1.3	
	Surp.	1.3	2.9	0.8	-	-	-	-	4.8	-	-	-	-	9.8
	Def.	-	-	-	13.0	6.5	6.5	0.9	-	3.0	1.4	0.5	1.6	17.6
5.0	St.	5.0	5.0	4.7	0.5	-	-	-	5.0	0.7	3.4	3.9	5.0	
3.4	Surp.	1.3	2.9	0.8	-	-	-	-	1.0	-	-	-	0.5	6.7
	Def.	-	-	-	-	5.9	6.5	0.9	-	-	-	-	-	12.4
10.0	St.	10.0	10.0	9.8	5.6	-	-	-	6.1	1.8	4.5	5.0	4.1	
2.4	Surp.	1.3	2.9	0.8	-	-	-	-	-	-	-	-	-	5.0
	Def.	-	-	-	-	5.9	6.5	0.9	-	-	-	-	-	13.3
15.0	St.	13.9	15.0	14.9	10.7	4.1	-	-	6.1	1.8	4.5	5.0	4.1	
12.6	Surp.	-	1.6	0.8	-	-	-	-	-	-	-	-	-	2.4
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
19.2	St.	20.5	23.5	24.1	19.9	13.3	6.8	5.8	11.9	7.6	10.3	10.8	12.5	
	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

* Environment Canada, Monthly Meteorological Summaries, 1976.

able often occurring earlier and often later. Snow not only provides moisture for recharge but also provides water for surplus. Snow is held as detention storage approximately until mean temperatures rise above 0° centigrade and then this moisture is released in a short time period (i.e. usually 2 to 3 weeks) acting much like a single precipitation event.

By late April, potential evapotranspiration is normally greater than precipitation and moisture held in the root zone of the soil is used for evapotranspiration (Figure 5.1). Potential evapotranspiration is greater than precipitation during the summer months and a continual drawdown of soil moisture takes place until a deficit occurs in late July. Using the bookkeeping procedure, soil moisture storage has reached zero, the lowest possible value, although under actual field conditions a small amount of moisture may be left for evapotranspiration. In September potential evapotranspiration drops below precipitation and a period of soil moisture recharge begins lasting through the winter. During this time very little precipitation is available for runoff as the soil moisture is recharged and moisture is stored as snow. The only runoff available will occur from the lower storage capacities of 1.3 centimeters and 5 centimeters or when precipitation exceeds the infiltration capacity of the soil. These lower storage capacities are representative of rooftops, parking lots, heavily packed areas, roads, and cleared areas near the construction site. Further discussion of yield from these areas is included in section 5.3.

The water balance patterns presented in figure 5.1 represent average year surpluses and deficiencies. This yearly water balance is based on

average mean monthly temperature and precipitation data for the period 1945 through 1975. These yearly patterns are not necessarily the same as the average surplus and deficiency because these "averages" were based on the actual patterns which occurred from 1945 through 1975. Surpluses are largely the products of the wet months, not average months.

During the period 1971 to 1976 a wide range of water balance patterns was present. Nineteen Seventy One was a very dry year as evidenced by the large deficits occurring in the summer (figure 5.2). By February all storage capacities were full and almost 9 centimeters of water held in detention storage as snow, were available from the 1.3 centimeter and 5 centimeter soil moisture storage levels (table 5.1). By March 31 there were 2 centimeters of precipitation in snow detention storage over soils which have a capacity to store 25 centimeters of water. Although all soil moisture storage levels were full and surpluses were being held in detention storage major flood runoffs were not recorded in north-eastern Alberta because of the very low precipitation in March, April and May of 1971. From April until October potential evapotranspiration was greater than precipitation and surpluses held in soil moisture storage were rapidly utilized for evapotranspiration. Deficits began occurring in the lower soil moisture storage levels as early as April and all moisture held in the 25 centimeter storage level was depleted in early June. A comparison of figures 5.1 and 5.2 shows that, in the 10 centimeter storage level, deficits occurred over a month sooner in 1971 than those noted in an average year. The deficit period not only started earlier than normal in 1971 but also lasted over a

month longer in 1971 than in the average year (figures 5.1 and 5.2). It can be seen that supplemental moisture would be needed in a year such as 1971 to support the growth of revegetated sites as these areas would have storage capacities of 2 to 4 centimeters.

In 1972 water balance patterns were similar to the long term normal patterns. Soil moisture recharge took place rather early in the year with surpluses developing in the 10 centimeter soil moisture level by early February. Although more than 10 centimeters of moisture was available for surplus in the 10 centimeter storage level, full recharge did not occur in the higher storage levels of 15 centimeters and 25 centimeters. Precipitaton was more evenly distributed in 1972 than any of the other years shown in figures 5.2 to 5.7 and tables 5.1 to 5.6. A double peak in potential evapotranspiration occurred in June and August with a decrease in July, unlike any of the other years presented. Cool temperatures in September reduced potential evapotranspiration to levels lower than the average (figure 5.1) and allowed soil moisture recharge to begin early in the fall. Areas with a 10 centimeter storage level were providing surplus, as snow in the detention storage, by early November. Precipitation, providing surpluses at the lower storage levels, was being used to recharge the 15 centimeter and 25 centimeter storage levels which had been completely depleted in the summer of 1972.

A wetter than average year is illustrated in figure 5.4 and table 5.3. By January of 1973 all soil moisture storage levels were filled to capacity except the 25 centimeter storage level. By the end of March detention surplus in the form of snow ranging from 13.3 centimeters

(water equivalent) in the 1.3 centimeter storage level to 4.8 centimeters (water equivalent) in the 15 centimeter storage level was available for runoff and ground water recharge during and after snowmelt. These surpluses did not provide a very large yearly flow because precipitation amounts were light during the snowmelt period. Discharge from the Hangingstone River was also low during and after the snowmelt period. With soil moisture storage levels at field capacity and surpluses available from snowmelt there was a high potential for at least localized flooding in Beaver Creek Basin. This situation provided potentially serious erosion problems from disturbed areas on the construction site and along the west interception ditch. More discussion on the discharge components of the water balance patterns is included in section 5.5.

Potential evapotranspiration was greater than precipitation for only a three month period of April, May and June in 1973. Thus, there was a short period when soil moisture utilization was necessary for optimum growth of vegetation. Unlike most years soil moisture recharge began in July when deficits normally occur caused by the maximum potential evapotranspiration rates at this time of year. Soil moisture recharge lasted until early October when surpluses occurred in soils with a moisture holding capacity of 10 centimeters or less (table 5.3). In 1973 deficits occurred at the lowest soil moisture storage levels; the lowest storage level, 1.3 centimeters, consists of parking lots, roof tops, and other paved or packed areas on the construction site, while the 5 centimeter storage level consists of areas with sparse grass cover, the dam and interceptor ditches, as well as areas recently revegetated.

During all of the summer of 1973, runoff corresponded closely to precipitation events. At no time did a deficit occur, so many of the rains recharged the soil with a moisture capacity of 10 centimeters or less, a number of times. The recharge and surplus patterns present in the later months of 1973 provide a basis for predicting record runoff in the spring of 1974. There was good soil moisture storage carry over from 1972 (figure 5.3 and table 5.2) in the higher soil moisture storage levels and soil moisture recharge began much earlier than in any other year (figures 5.1 to 5.7) generating surpluses before the end of 1973. This pattern set the stage for flooding and high stages of discharge which took place throughout much of northern Alberta and especially in an area extending from Edmonton to Fort McMurray on into north-western Saskatchewan. A.H. Laycock (1974) used water balance procedures developed by Thornthwaite (1948, 1957) to forecast high runoff in the spring of 1974. By analysing water balance patterns previous to 1974 Laycock (1974 p. 1) stated that there was "a greater potential for high spring runoff than in any previous year since 1902." Water management decisions could have been altered with this high flow forecast. Erosion potential was high on all cleared areas such as the interception ditch. Land disturbance would add to the sediment load originating from the cleared areas. Water yield would be greater than in almost any other year and decisions on management of this yield could have been made (e.g., pumping could be reduced from the Athabasca River with local surplus providing runoff to Mildred Lake). Problems of surplus disposal and reduction of erosion could be dealt with before they occurred (see section 6.3).

Surpluses were generated during the first three months of 1974 in all soil moisture storage levels (table 5.4). High discharge stages were maintained for over two weeks, from the 16th through the 31st of April (Figure 3.2). Precipitation in April amounted to 1.2 centimeters thus preventing the potential for extremely high flow. Precipitation although below average, was well distributed throughout the summer months and soilmoisture utilization at the 10 centimeter storage level lasted until late August. Above normal temperatures allowed evapotranspiration to continue and exceed precipitation through October. Potential evapotranspiration was over 2.5 centimeters (table 5.4) in October and a deficit occurred until late October when potential evapotranspiration dropped below precipitation (Figure 5.5). No deficits occurred in the 15 centimeter and 25 centimeter soil moisture storage levels, as sufficient soil moisture was available in carry over from 1973.

The water balance pattern of 1975 is unlike any of the other patterns in the period 1971 to 1976 (Figures 5.1 to 5.7). Although precipitation was above normal for the year (i.e. 59.7 centimeters versus 43.7 centimeters) no surpluses were generated in the spring at the 10, 15 and 25 centimeter soil moisture storage levels because precipitation was light (7.8 centimeters) during the first quarter of the year when the potential for surplus production was greatest (table 5.5). High potential evapotranspiration rates in the fall of 1974 also prevented soil moisture recharge from beginning until November. Soil moisture utilization began late in May and continued until late August when low potential evapotranspiration and above normal precipitation produced a recharge period lasting

until mid-December. Thus no surplus was produced in the spring of 1975 and no deficit was produced in late summer or early fall of 1975 in soil moisture storage levels of 10 centimeters or more.

Early in 1976 small surpluses were available for runoff at the time of spring snowmelt in areas with the lower soil moisture storage capacities. The potential for above average runoff existed but low precipitation was received from March through May (i.e. 3.8 centimeters which is 50 percent of normal) when soil moisture storage levels were near field capacity (table 5.6). Exceptionally high potential evapotranspiration rates occurred in April as the monthly mean temperature was 6° centigrade above normal. This rapid use of soil moisture was responsible for the deficit situation which began in mid-June (figure 5.7) for soils capable of providing 10 centimeters of storage. A general draw down of soil moisture, from field capacity levels reached during the spring of 1974, occurred throughout early and mid-summer of 1976. Soil moisture recharge began in late summer as 11.5 and 17.3 centimeters of precipitation were recorded in July and August respectively, at Fort McMurray. A cross check of meteorological data collected at Mildred Lake and Thickwood Hills shows that precipitation was well above normal during July and August although amounts recorded at Fort McMurray are higher than those recorded in the rest of north-eastern Alberta. High potential evapotranspiration in late August and September provided another period of soil moisture utilization before soil moisture recharge began in mid-October in soils with a 10 centimeter moisture capacity.

Very little surplus was available for runoff during the summer field

season of 1976. Snowmelt runoff provided very little runoff as less than 20 percent of the total yearly runoff was recorded in April and May. In field trips to the study area a steady low stage discharge was evident from May into early August (Figure 3.4). Soil moisture storage levels were at zero in all storage categories except the 25 centimeter storage level (5.7 centimeters in storage) by July of 1976. Precipitation amounting to 7.2 centimeters between July 7 to the 13 provided very little surplus at all using water balance procedures (Figure 3.4). Actually the maximum yearly discharge of 1976 occurred in August. Part of the surpluses generated in August originated from the high intensity of the rainfall (i.e. 9.4 centimeters on August 25) and the inability of the lower soil moisture storage levels to hold the precipitation. The greater part of the surpluses generated came from the muskeg areas which had reduced evapotranspiration rates, thus leaving moisture in storage (see section 5.3 for further discussion).

Much of the soil moisture recharge which occurred in late August and early September was utilized by evapotranspiration in late September and early October, as temperatures were above normal. Soil moisture carry over from 1974 and 1975 was almost completely used by late fall of 1976. Precipitation in November and December of 1976 amounted to only 2.4 centimeters, while January, 1977 produced only half a centimeter. Although precipitation amounts for February, March and April are not yet published they were relatively light. Bearing this in mind it seems certain that snowmelt runoff will be much the same as in 1976. Widespread rains would be needed to generate high discharges. Thus, any

activity (i.e. construction work) depending on a relatively dry soil will probably be able to begin early this spring. Unless irrigation is planned any areas revegetated will have very little subsoil moisture to draw upon. A daily water balance could be used as a continuing forecast base to aid in revegetation scheduling and also as a guide for irrigation scheduling.

5.3 Beaver Creek Basin Yield

Yield patterns within the study area tend to fluctuate widely from year to year, with the smallest streams showing the greatest variability. In most years snowmelt makes a significant contribution to the yearly yield because of detention storage provided. During the past field season basin yield was lower than in any of the four previous years which were above average. Runoff ceased during February and after only marginal snowmelt discharge was dependent on ground water discharge and muskeg drainage in early and mid-summer as observed during field trips in the study area. Major basin yield during the summer field season was limited to one major storm period from the 25th to the 28th August. Thus, yield patterns were much different in 1976 than in the preceding years, 1972 to 1975.

Estimates of yield for the period 1972 to 1975 are presented in tables 5.7. It should be noted total land area in each soil moisture storage category is not consistent in the table. These different estimates have been made to account for the dynamic changes which have taken place within the study area in the last five years and which are continuing

Table 5.7: Estimated Basin Yields - Using Thornthwaite Water Balance and Future Land Use Changes.

1972

Percentage of Land Area in Storage	Storage Capacity	Area (Hectares)	Yield (Cm)	Surplus (HMY)
3%	½'' (1.3 Cm)	1,306	27.8	363
10%	2'' (5 Cm)	4,355	17.9	780
20%	4''(10 Cm)	18,709	10.3	1,879
35%	6''(15 Cm)	15,240	5.2	793
37%	10''(25 Cm)		0	0
	Total Estimated	43,546	6.5	2,815
	Total Gauged	43,546	5.9	2,564

1973

Percentage of Land Area in Storage	Storage Capacity	Area (Hectares)	Yield (Cm)	Surplus (HMY)
5%	½'' (1.3 Cm)	2,177	36.4	792
15%	2'' (5 Cm)	6,532	21.2	1,385
20%	4''(10 Cm)	18,709	14.7	1,280
30%	6''(15 Cm)	13,063	14.0	1,828
30%	10''(25 Cm)	13,063	13.3	1,737
	Total Estimated	43,546	16.1	7,022
	Total Gauged	43,546	16.3	7,121

Table 5.7 continued

1974

Percentage of Land Area in Storage	Storage Capacity	Area (Hectares)	Yield (Cm)	Surplus (HMY)
10%	½" (1.3 Cm)	4,355	16.3	710
20%	2" (5 Cm)	8,709	13.8	1,206
20%	4" (10 Cm)	8,709	13.8	1,201
25%	6" (15 Cm)	10,886	13.8	1,502
25%	10" (25 Cm)	10,886	13.3	1,447
	Total Estimated	43,546	13.9	6,066
	Total Gauged	43,546	12.6	5,473

1975

Percentage of Land Area in Storage	Storage Capacity	Area (Hectares)	Yield (Cm)	Surplus (HMY)
10%	½" (1.3 Cm)	4,355	20.5	893
20%	2" (5 Cm)	8,709	8.1	705
20%	4"(10 Cm)	8,709	0	0
25%	6"(15 Cm)	10,886	0	0
25%	10"(25 Cm)	10,886	0	0
	Total Estimated	43,546	3.7	1,598
	Total Gauged	43,546	13.9	6,051

Table 5.7 continued

1976

Percentage of Land Area in Storage	Storage Capacity	Area (Hectares	Yield (Cm)	Surplus (HMY)
1%	½" (1.3 Cm)	163	13.5	22
4%	2" (5 Cm)	653	9.7	63
20%	4"(10 Cm)	3,266	9.6	248
40%	6"(15 Cm)	5,715	2.5	143
35%	10"(25 Cm)	4,899	0	0
	Total Estimated	14,696	3.2	476
	Total Gauged	14,696	13.6	2,214

to take place. These estimates have been made to provide an average of the soil moisture storage levels which existed throughout the Syncrude Lease in each year.

Soil moisture storage capacities presented in table 5.7 (1972) are representative of the patterns present before man altered the surficial materials and vegetative cover. This is not to say that natural changes such as forest fire and disease do not alter soil moisture storage levels through time. Very little land is placed in the 1.3 centimeter and 5 centimeter storage category with the greatest percentage of the study area being placed in the 15 centimeters and 25 centimeter soil moisture storage levels. The 5 centimeter soil moisture storage level was used to account for large areas of muskeg which have 25 centimeters of soil

moisture storage but have only 5 centimeters of moisture available for evapotranspiration. Laycock (personal communication, 1977) has suggested that much of the muskeg in north-eastern Alberta provides moisture in the top few centimeters for evapotranspiration with moisture below in semi-dead storage. Even though the total storage level is 25 centimeters the insulating effect of the muskeg produces yields comparable to the 5 centimeter storage level. A gradation in soil moisture storage capacity exists, as muskeg with very little tree cover and a sparse hummocky sedge meadow surface cover would have the greatest amount of dead storage. Forested areas would have 5 centimeters to 10 centimeters of soil moisture storage rather than well drained forested areas with 15 centimeters to 25 centimeters of storage.

This insulating blanket of largely dead organic material reduces evapotranspiration to some percentage (e.g., 30 to 60 percent) of potential evapotranspiration eventhough water is not a limiting factor. Vegetation cover in these areas has less than optimal growth because of the saturated condition within the root zone. The insulating organic cover also helps provide for slow melting of ice and soil frost below the surface, thus cold water provides for reduced transpiration rates. One alternative of dealing with this problem would be to use something less than 100 percent of the estimated potential evapotranspiration in water balance procedures for areas with large amounts of muskeg. Therefore, drawdown of soil moisture storage would take place much slower than in areas with better drainage and surpluses such as those in August 1976 would not be wholly unexpected.

Major land use changes took place in 1973 and 1974 as clearing and construction began on the Syncrude extraction plant site. Clearing took place on the relatively flat poorly drained table land above the escarpment of the Athabasca River. Removal of forest cover plus the compaction of surficial materials lowered the soil moisture storage capacity of disturbed areas. Land formerly in the 15 centimeters and 25 centimeter storage categories was placedin the 1.3 centimeter and 5 centimeter storage level as clearing and ditching took place. Therefore, the percentage of land area in the higher soil moisture storage levels began to decrease causing a change in yield patterns.

A major change in percentage of land area in each storage category as well as a change in total land surface drained can be noted in table 5.7 (1976). Water Survey of Canada's gauging site was changed from below the Syncrude site to a new site located upstream from the plant site and draining an area 163 square kilometers. The altered drainage basin drains soils with a greater capacity to hold water than those areas previously drained. Yield patterns in the unaltered part of Beaver Creek Basin are discussed in reference to water management alternatives (section 6.3).

Estimated yield is in close agreement with gauged runoff for the period 1972 to 1974. Basin yield is somewhat higher than the author expected as the surpluses presented in the table were derived from daily water balance computations using Fort McMurray meteorological data. Data from the Mildred Lake Site was not used because the full period of data was not available as data collection did not begin until the summer of

1973. Also the author is skeptical of the data collected as the site was moved several times from the mine pit itself to areas adjacent to the construction site. Lower yield may be expected for Mildred Lake if yearly precipitation data for Mildred Lake and Fort McMurray, as presented in table 5.8, are correct.

Table 5.8: Yearly Precipitation - Mildred Lake Versus Fort McMurray*

Precipitation in Centimeters

Year	Mildred Lake	Fort McMurray
1976	32.1	51.5
1975	60.0	59.5
1974	35.0	44.4
1973	41.9	43.6

* Source: Environment Canada, Monthly Record of Meteorological Data (1973-1976).

A cross check of estimated yield per unit area in Beaver Creek with gauged runoff of the Hangingstone River Basin showed close correlation, with the Hangingstone River providing a greater per unit area basin yield in 1972 through 1974 (table 3.2).

A very poor relationship exists between estimated runoff and gauged runoff from Beaver Creek Basin in 1975 (table 5.7). Of the categories listed, only the 1.3 centimeter and 5 centimeter soil moistrure storage

levels showed any yield at all in 1975. High potential evapotranspiration and low precipitation in the latter half of 1974 provided for a major drawdown of soil moisture in storage. In early 1975 all of the precipitation was used for recharge of the soil moisture except in the 1.3 centimeter and 5 centimeter storage levels. Precipitation was evenly distributed throughout 1975 providing frequent recharge periods but not providing surpluses in storage levels greater than 10 centimeters. Some of the gauged surplus can be attributed to the lower potential evapotranspiration and greater precipitation in the upland of the Thickwood Hills. Soil moisture utilization in the uplands was not as great as in lower reaches of the basin during 1975. Soil moisture carryover from the wet years of 1973 and 1974 was greater in the Thickwood Hills than in lower reaches of Beaver Creek Basin. Instead of the frequent near capacity levels achieved in the lower parts of the basin, surpluses were generated in the uplands. Interflow within the muskeg from the two previous wet years also added to the unexpectedly high yields of 1975. Many areas of depressional storage, which in most years do not contribute yield, were at capacity levels and were also adding to the high yield. Again in 1975 a reduced evapotranspiration rate masked the actual water balance pattern of muskeg areas as substantial contribution to surpluses occurred as storage capacity levels were exceeded many times. Further study is needed before actual evapotranspiration as a percentage of potential evapotranspiration be determined.

Data gathered from the Water Survey of Canada during the summer months of 1975 are questionable because frequent rapid discharges would be

very difficult to gauge manually. A coffer dam constructed to restrict flows while work took place on the north starter dyke failed a number of times releasing large volumes of water such as the mean daily discharge of 54 cubic meters per second recorded on July 18, 1975 (Figure 3.3). The author is not questioning the excellent data collection work done by Water Survey of Canada personnel but gauging under conditions previously mentioned would be very difficult.

Inaccurate gauging of precipitation could have also been a factor in 1975. Undercatch of snowfall may run as high as 60 percent under wind speeds of 11 meters per second, while under the same conditions there may be a deficiency of 40 percent for rainfall (Gray, 1974). Woodburn (1977) found that adjustments for snowdrifting were necessary if using Thornthwaite procedures, especially in the dryer years.

Beaver Creek Basin had a low yield of 476 hectare-meters in 1976 which would have covered the basin to a depth of 3.6 centimeters. Again during 1976 a drawdown of moisture in a storage took place in areas with higher storage capacities. Soil moisture levels in the uplands would not have been as low. Thus, two reasons account for the relatively large difference between gauged and estimated discharge: first, yields were greater per unit area in the uplands than those shown in table 5.7; second, over 50 percent of the total discharge of 1976 was generated in late August and early September following 9 centimeters of rain on August 26, with over 15 centimeters of rain recorded from August 25 through September 7.

Many yield patterns are present in all years in which gauging data

were available. High yields in all years from the lower soil moisture storage categories are pronounced. Yield from the 1.3 centimeter storage level provided half the surplus derived from either the 10 centimeter or 15 centimeter storage level from only one fourth as large a land area. In a wet year such as 1973, 5 percent of the basin (i.e. 1.3 centimeter storage capacity) produced nearly half as much runoff as 30 percent of the basin (i.e. 25 centimeter storage capacity). Even in a dry year a sizeable surplus may be generated from the lower storage levels, especially if snowfall is close to normal.

Yield differentiation patterns are indicated in table 5.7 (1972 and 1976) as per unit area yield decreases with increased soil moisture storage capacity. The lower storage categories of 1.3, 5 and 10 centimeters, in 1976, covered 25 percent of the surface area in Beaver Creek Basin yet they provided almost 70 percent of the estimated runoff. Higher soil moisture storage areas provided only 25 percent of the estimated runoff in 1976. In the relatively wet years of 1973 and 1974 yield differentiation was not as noticeable because all storage levels contributed to runoff and although per unit area runoff was less in the higher storage areas the greater percentage of land area compensates so that the largest surpluses are derived from the higher soil moisture storage areas.

In drier years, yield differentiation would be significant with almost no runoff generated from the higher storage areas. High potential evapotranspiration in these years would produce a draw down in soil moisture and the surpluses would be produced almost wholly from the lower

storage capacity areas. Many of the areas of muskeg would provide relatively high yield contributions in the drier years because of the insulating effect of the organic layer on the surface. The moisture below the surface remains cool and frost persists well into summer. Thus, evaporation rates are low in the still air within the organic blanket.

5.4 Variation in Yield

To date very little work has been done on variation in yield in Beaver Creek Basin or for that matter in any of north-eastern Alberta. Data presented in section 3.2 showed the variation in yield of the Ponton and Boyer Rivers in north central Alberta. Kellerhals (1973) did a preliminary study to determine stage discharge relationships, for tributaries of Beaver Creek as shown in Figure 1.3. No gauging of snowmelt runoff was done and only periodic gauging was carried out in the summer of 1973 by personnel of Syncrude and L.G.L. environmental consultants. None of their findings are surprising nor do they contradict patterns indicated by the use of water balance procedures.

The highest per unit area runoff was derived from Creek Four which has its headwaters in the uplands where potential evapotranspiration is lower and precipitation is greater because of orographic uplift. Kellerhals (1973) found that discharge rates are higher in Beaver Creek Basin than in those of Creeks One, Two and Three and this can be explained by the greater runoff rates experienced in the upper Beaver Creek Basin. The greatest runoff per unit area is probably provided by Cache Creek, originating near the divide in the Thickwood Hills and having the

greatest percentage of its basin area in the uplands. In summary the highest runoff rates are generated from streams originating in the uplands owing to a decreased potential evapotranspiration and increased precipitation. The lower Creeks One, Two and Three have lower runoff rates than those of the upland and also have very poor land drainage. Snowmelt runoff detention storage is also provided by the numerous beaver dams on these lower Creeks.

5.5 Daily Versus Monthly Surplus and Deficiency Patterns

One of the major drawbacks in the use of water balance procedures is that monthly bookkeeping procedures often mask many of the patterns which occur during the month. Daily water balance computations showing short term changes in water balance patterns were undertaken during the summer field season using meteorological data from Fort McMurray. A thirty one year period, 1945 to 1976, was used as a data base. Water balance procedures adopted by Thornthwaite (1948) were used in the bookkeeping proceudre as well as his method of estimating potential evapotranspiration. Inaccurate estimation of potential evapotranspiration, especially for a period as short as one day, using an empirical formula is a major concern of many researchers. The author made no attempt to estimate the short term accuracy of potential evapotranspiration estimates but used them as an indicator of the relative wetness or dryness of the study area.

Yearly estimates of potential evapotranspiration on a monthly data basis were as much as 5 centimeters less than estimates made using daily

data. In most years potential evapotranspiration using daily data is 1 centimeter to 2 centimeters greater than totals of potential evapotranspiration using monthly data. Higher potential evapotranspiration estimates using daily data occur in part when the mean monthly temperature is below 0° centigrade (i.e. potential evapotranspiration is assumed to be nil) yet a number of days during the month have mean daily temperatures well above 0° centigrade with evapotranspiration taking place. April and October are the critical months in the Beaver Creek Basin as mean monthly temperatures are usually near 0° centigrade. Monthly evapotranspiration rates underestimate the true water need in these months. A number of days throughout the winter also have daily mean temperatures above 0° centigrade, thus providing additional evapotranspiration not shown using monthly data. Although estimates of potential evapotranspiration using daily data are higher than those using monthly data, deviations in estimates are not nearly so great as in regions of southern Alberta where warming chinook winds in fall, winter and spring can provide significant potential evapotranspiration rates. This potential evapotranspiration would not usually appear as monthly mean temperatures which would be below freezing.

Variations in distribution of precipitation during the month and not deficiencies in estimates of potential evapotranspiration provide the largest variation between daily and monthly water balance patterns. Surpluses using a daily water balance, from land surfaces capable of 1.3 centimeters of moisture storage, averaged 19.3 centimeters or 46 percent greater than surplus estimates made using monthly data. In the

1.3 centimeter storage level surplus has been as much as 17 centimeters greater using daily estimates compared to estimates made using monthly procedures (Appendix II). Thus, average yield per unit area is much greater from these relatively low storage areas, especially where surfaces have been made relatively impervious by construction activities.

Although not as pronounced, similar surplus patterns exist for storage levels up to and including the 10 centimeter soil moisture storage level. In an average year very little difference in surplus estimates exists in higher storage categories.

Surpluses from the lower storage levels are usually derived from a storm or storms providing anywhere from 5 to 10 centimeters of rain over a one or two day period. During these storms soil moisture storage is filled to capacity and surpluses occur. Field capacity is exceeded for the lower soil moisture storage levels for these storms. Hence, if daily water balance procedures are used these surpluses are evident.

Using monthly water balance procedures these surpluses from moderate to heavy storm events may not be apparent. Total precipitation for the month may be less than potential evapotranspiration and surpluses would not apparently be generated. Thus, very little surplus is provided using monthly water balance procedures when in fact surpluses actually occurred. If the higher soil moisture storage areas were charged to near capacity they would also be shown as contributing surpluses with extra precipitation if daily procedures were used.

Deficits are also much greater using daily data, especially in the lower soil moisture storage levels. This pattern is evident if table 5.6

is compared to the monthly water balance in Appendix II as precipitation for the month of August totalled 17 centimeters yet a deficit of 2.5 centimeters occurred in the 5 centimeter and 10 centimeter storage level while a deficit of 5 centimeters occurred in the 1.3 centimeter storage level. Irregular distribution of precipitation permits both deficits and surpluses to be recorded in the same month. Thus, during the course of a month a revegetated site (e.g., with a 5 centimeter storage level) could suffer from drought and also provide surplus for runoff. These differences in daily and monthly water balance patterns show that for better knowledge of surplus and deficit patterns daily estimates are a superior indicator of the true pattern. For future water resource management, whether it be for estimating basin yield or estimating water need for revegetated sites, a daily water balance should be used.

CHAPTER VI

Water Management Alternatives

6.1 Introduction

In previous chapters discussion has been focussed upon the physical setting, basin hydrology, water balance equation and water balance patterns of the Beaver Creek Basin. This prior knowledge is necessary as baseline data for determination of future water balance changes brought about by land use changes. Water management decisions should be based in large part upon knowledge of prior water balance patterns as well as expected future water balance patterns. In section 6.2 future regime and yield patterns are presented and discussed using existing precipitation data. Tentative suggestions are made for future plant and mining operations relating to those patterns. Discussion in section 6.3 centers on water management alternatives which may be useful in planning plant operations bearing in mind environmental considerations. In the last two sections (6.4 and 6.5) off site alternatives and alternatives in the Thickwood Hills are presented.

6.2 Water Management - To The Present

Very little integrated water management has taken place in Beaver Creek Basin. Syncrude Canada Ltd. had two main underlying criteria governing water management decisions: first, a reliable high quality source of water is needed for the extraction process; and second, by

government regulation no precipitation falling upon or runoff originating from disturbed land areas as well as water used in the extraction process shall leave Crown Lease No. 17 without special short-term permits which may be increasingly hard to obtain. The Athabasca River provided a reliable source of water which is of high quality during most of the year (i.e. at spring breakup suspended sediment loads are too high to permit use without storage in a settling basin). Syncrude policy requiring an internal drainage system in and near the mining area necessitated construction of Beaver Creek Dam, the north starter dyke, and diversion of tributaries from the west and north into the west interception ditch. Laycock (1974) noted that two problems have inhibited development of water management alternatives. One problem is that government regulations have impeded development of alternatives. As long as all water originating in and near the plant is required to be disposed of within the lease area problems will likely occur. This excess water is pumped into the tailings ponds which are an area of concern to Syncrude, government and environmental personnel, although much of the surplus is as high or higher in qaulity than water currently discharging from Beaver Creek. Should these coarse waste and sludge tailings be piled high on 31 square kilometers of mineable oil sand or could disposal areas on lands of low productivity be used north of the study area? These high tailings piles on the Syncrude Lease may not only be aesthetically unpleasant; they may also present a severe erosion potential (Syncrude, 1977). The second problem is the degree of secrecy concerning research maintained by both government and industry. As Laycock (1974, pp. 198) states: "Secrecy

merely results in duplicate effort, specific non-integrated research, and decisions without proper review by too few people. The costs of operation are greater and inflexibility in policies becomes entrenched." Great Canadian Oil Sands and Syncrude projects are both observed as prototype plants for economic reasons and more importantly as potential models for evnironmental management practices. Therefore, both government and in house members should work toward a better exchange of information and ideas.

Syncrude's (1976, forwarding statement not paginated) environmental policy has been presented as follows:

> Syncrude Canada Ltd. works with the conviction that human use of the environment need not be destructive. With careful planning, based upon good information, man-altered and natural ecosystems can exist in harmony. In order to accomplish this planning, Syncrude considers resource development from a total-systems point of view. This comprehensive approach corrects the frequent tendency to attempt resolution of problems on a single purpose basis. The total-systems analysis approach leads to a plan of operations using the best practicable technology, both in resource development and in environmental protection. An ecosystem approach to resource development, an integral part of our approach, implies an understanding of and respect for the potential of natural systems and the use of economy of nature, wherever possible.

Thus, "careful planning", for water management, requires prior, as well as, future knowledge of regime and yield patterns in Beaver Creek Basin. Future water management decisions should follow this "comprehensive approach" and resolution of water problems should not take place on a single purpose basis if at all possible. Water management decisions should be based on this "total-systems" analysis whereby mining, operations, and environmental protection sectors development policies

might be made in accord with one another and not as individual problems.

Multiple purpose projects are being constructed in an effort to use water resources efficiently and multiple means should be used in conjunction with multiple purpose projects for better management. Senate document No. 97 directed that: "Planning for the use and development of water and related resources shall be on a fully comprehensive basis so as to consider . . . (2) all relevant means (including non-structural as well as structural measures) singly, in combination, or in alternative combinations reflecting different basic choice patterns for providing such uses and purposes". (Senate Document No. 97, pp. 3, from White, 1969). If water resource management in Beaver Creek Basin is going to be comprehensive in nature non-structural as well as structural alternatives need to be considered to deal with the increased volume of runoff expected with land-use modification. Before any management decisions are made, objectives concerning Syncrude's operations should be reviewed as well as government regulations affecting the operation.

6.3 Future Water Yield and Regime Patterns

Modified Drainage Area

Three separate drainage systems now comprise what was formerly the Beaver Creek Basin. An area of 164 square kilometers is drained by the headwater tributaries and Beaver Creek above the new gauge site. This area has not undergone major land-use changes and flow from this system now enters the Athabasca River via Beaver Creek Reservoir and Poplar Creek Diversion. Discharge from Beaver Creek into the Poplar Creek

Diversion is not used in the plant mining or extraction processes but serves at present (by special permit) as a means for dilution of saline water originating from mine depressurization. Yield and regime patterns in the upland areas will be discussed as they relate to water management alternatives in section 6.

The west interception ditch diverts flow northward from Creek One, Two and Three into Bridge Creek just north of lease 17 boundary. Approximately 12,960 hectares or nearly one-third of the original Beaver Creek is drained or modified by this altered system. This area has a water management potential which could enhance future mining operations (e.g., muskeg drainage preparatory to mining) as well as stimulate the growth of vegetation. Water management alternatives for this drainage area will be included in section 6.4.

Crown Lease No. 17 covers an area of approximately 20,000 hectares of land located in the drainage basins of the MacKay River and Beaver Creek. Roughly 12,500 hectares will be modified with development, with the area formerly having been covered with muskeg and woodland having soil moisture storage utilization levels of 5, 10 and 25 centimeters. Water yields under average and recent year climatic conditions were low to moderate in most years with the earlier 1970's being the exception as high yields were obtained from the high storage areas. One major concern of both Syncrude personnel and government officials is the increasing estimate of land area required for tailings disposal. In 1962 consideration was given to using Horseshoe Lake in the Athabasca Valley as a tailings disposal site because this would have prevented placing tailings

over a mineable sand formation. By 1968 estimates for a tailings disposal area of over 7.7 square kilometers was made with the new location being just north of the plant site as shown in Figure 1.2. Current estimates call for a plant extraction tailings area of 29 square kilometers with an additional 4.4 square kilometer pond used for Froth Treating Plant Tailings. Any reduction in the size of these tailings ponds would provide a two-fold benefit; mineable oil sand formation would not be covered, thus it would be available for easier future mining and smaller ponds and dike areas would be easier to manage.

In table 6.1 a summary of all water originating in or falling on the plant extraction and mining area is presented with (b) and (c) of the inputs being the most variable. Estimates of (d), (e), (f), and (g) are still being studied but, once correctly determined, variability from year to year should not be as great as is indicated. Water balance patterns estimated by Syncrude are shown in table 6.1, column 1, with Laycock's estimates in columns 2 and 3 (Syncrude, 1971 and Laycock 1974). The author's estimates for both wet and dry years, columns 4 and 5, are slightly higher than Laycock's estimates and both are much greater than Syncrude estimates. Estimates in columns 4 and 5 were based on Thornthwaite procedures using daily water balance computations. Wet year estimates were based on yield for 1972 while dry year estimates were based on yield data from 1975, both using tentative land-use estimates for near the year 2000 A.D.

Estimates in columns 4 and 5 are greater than those in columns 2 and 3 because yield using daily procedures is greater than estimates made

Table 6.1: Net Summary of Internal Hydrologic Cycle of Syncrude Operation[1]

(Hectare Meters)

In:	Syncrude's * Estimate	Laycock's Estimate wet year**	Laycock's Estimate dry year**	Author's Estimate wet year	Author's Estimate dry year
a) Pumping from Athabasca River	4201	2823	4235	2823	4235
b) Runoff to Mildred Lake	45.1	293	87	325	91
c) Runoff to tailings Ponds	138.4	912	273	977	276
d) Water in Overburden		533	533	533	533
e) Water in Oilsands	369	1479	1479	1479	1479
f) Water in Reject		991	991	991	991
g) Percolation - to Mine		84	56	84	56
Totals	4754	7115	7654	7212	7661

* Taken from Syncrude's Environmental Impact Assessment - 1973.
** Laycock used Thornthwaite procedures on a monthly basis.
[1] Authors estimate used Thornthwaite procedures on a daily basis using modified drainage area of 10,368 hectares.

Table 6.1 Continuation

Out	Syncrude's * Estimate	Laycock's Estimate wet year**	Laycock's Estimate dry year**	Author's Estimate wet year	Author's Estimate dry year
a) Evaporation: Upgrading Plants	1239	1214	1270	1214	1270
b) Extraction Plant	79	79	79	79	79
c) Natural Evaporation: Tailings Ponds		-392	657	-392	657
d) Natural Evaporation: p/c Ponds	197	-62	98	-62	98
e) High Temperature Pond Evaporation	194	705	847	705	847
f) Percolation (net)	197	282	169	282	169
g) Interstitial: Coarse & Reject	1939	1939	1939	1939	1939
h) Interstitial: Sludge	844	844	844	844	844
i) Interstitial: Froth Sludge	62	62	62	62	62
Total	4751	4609	5965	4609	5965
Surplus		2506	1689	2603	1696

using monthly procedures. A surface area of 10,368 hectares was used as contributing area of internal drainage to the tailings ponds and Mildred Lake, with these areas being modified to lower soil moisture storage capacity. As previously mentioned the daily water balance provides a much better approximation of yields from the lower soil moisture storage levels. Many factors (i.e. mining technology, future government regulations, or extraction processes) may change the proposed future drainage area considerably.

As previously mentioned there has been a growing concern by Syncrude officials, government personnel, and environmentalists about the expected increase in surface area needed for tailings disposal. Problems associated with this large tailings pond have included dyke leakage, winter ice fog, ground water pollution and hazards to waterfowl. In developing water management alternatives one objective of Syncrude should be to keep the tailings ponds as small as possible. Water management policies should be aimed at managing and reducing all variables on the inflow side of table 6.1. Reduction of inflow variables on the one hand should be complemented by a subsequent increase in the outflow variables to reduce the total surplus. (e.g., Totals: Inflow-outflow = surplus). Management of flow within the two categories is also possible but providing separate storage for the higher quality water. Laycock (1976) suggested that much of the water originating on site should be separated into quality classes to be used in the highest consumption class possible. Three alternatives could be developed: 1) delivery of locally derived surplus to the Athabasca River; 2) delivery of water to Mildred Lake settling basin for direct use;

3) delivery to recycling ponds where upgrading requirements are small and short term; 4) delivery to plant areas having low quality requirements. This reduction in tailings pond size could be complemented by studies of possible relocation of coarser tailings and sludge to low productivity areas north of the study area. This alternative is possible for the distant future but it would prevent future covering of potentially mineable oil sands. Thus, under current government regulation approximately as much surface area is needed for tailings disposal as is needed for mining purposes. Recovery of this would be possible but at relatively high cost. Pumping from the Athabasca River should be kept to a minimum even though it is a continuous source of good quality water in most months (i.e. spring break-up being the exception due to high sediment loading from snowmelt runoff). Excessive withdrawal from the Athabasca River only increases disposal problems in the outflow part of table 6.1. Presently, there is no pressing demand by other users for quality or quantity improvements of Athabasca River water. There is a possibility that heavy demands may be placed on the water of the Athabasca River in the future if heavy development were to take place. In the early 1970's rumor had it that as many as 20 extraction plants were to go into production by the year 2000 A.D. It seems almost certain that development will be much slower but we should use foresight and not waste this water. Heavy use of Athabasca River water for both future extraction and domestic uses could have a detremental effect on the highly productive Peace-Athabasca Delta.

If twenty oil sands extraction plants, with water requirements similar

to Syncrude Ltd., were in operation 84,000 hectare-meters of water would be required per year. This consumptive use water withdrawal would amount to over 20 percent of the average minimum flow of the Athabasca River below Fort McMurray. For comparison this water requirement for extraction purposes alone would equal one half of the mean annual discharge of the Red Deer River. Water management and disposal, even with a working knowledge of water balance patterns would be monumental.

Local supplies should be used in plant operations to the fullest extent possible since these yields cannot be limited to the same degree as pumping from the Athabasca River and disposal of them becomes a problem. One major problem with locally generated supplies is their variability as shown in table 6.2. Even in early stages of development, a dry year such as 1975 would provide 584 hectare meters of yield while a wet year such as 1972 would provide 2065 hectare meters of yield or four times the yield generated in 1975 (estimates were based on land-use changes in stage II of the development sequence). Greater extremes would be present in a longer period of record. The timing of this yield is also highly variable as in 1976 there was very little yield until August while in many years most yield will be generated in later spring and early summer.

Syncrude's estimates show 25 percent of local water yield being returned to Mildred Lake for later reuse with the remaining 75 percent entering the tailings ponds. Currently, no future land-use plan exists which could be used to put land into potential quality classes so it is very difficult to estimate the possible increase which could be made in high quality yield available for easy reuse. In wet years as much as 977

Table 6.2 Water Yields from Syncrude Land Areas in and Near the Plant, Mines and Ponds

(eg. 10,300 hectares)

(Assuming Average 1972, 1973, 1974, 1975, and 1976 Temperature and Precipitation and Three Stages of Development.)

Stage 1 - Pre Development e.g. 1970

Surface Area	Storage Cap. (cm)		Average	1972	1973	1974	1975	1976
1%	1.3	(½")	19.3	30.6	33.9	17.2	24.1	13.5
9%	5	(2")	95.5	261.	168.0	124.6	72.5	86.7
20%	10	(4")	118.	206.	293.6	276.	0	151.9
40%	15	(6")	120.9	208.	385	552	0	100.6
30%	25	(10")	25.	0.		399	0	0
100%			378.9	705.	880	1369	96.6	352.7
Yield in Centimeters			3.79	7.0	8.8	13.69	.97	3.5
Streamflow - hectare meters			460	850	1069	1663	117	425

Table 6.2 continued

Stage 11 - Early Development e.g. 1980

Surface Area	Storage Cap. (cm)		Average	1972	1973	1974	1975	1976
10%	1.3	(½'')	193	306	339	172	241	135
30%	2.5	(2'')	318	870	558	414	240	291
30%	10	(4'')	177	309	294	414	0	228
20%	15	(6'')	60	224	384	276	0	50
10%	25	(10'')	8.4	0	0	133	0	
100%			756	1709	1575	1409	481	704
Yield in Centimeters			7.6	17.	15.7	14.9	4.81	7.04
Streamflow - hectare meters			923	2065	1907	1711	584	855

Table 6.2 continued

Stage 111 - Late Development e.g. 2000

Surface Area	Storage Cap. (cm)		Average	1972	1973	1974	1975	1976
20%	1.3	(½")	386	612	678	344	482	270
35%	5	(2")	371	1015	651	483	280	339
20%	10	(4")	118	206	294	276	0	152
20%	15	(6")	60	112	192	276	0	50
5%	25	(10")	5	0	0	66	0	
100%			940	1945	1815	1445	762	811
Yield in Centimeters			9.40	19.45	18.15	14.45	7.6	8.1
Streamflow - hectare meters			1142	2363	2205	1755	923	984

hectare meters of water may enter the tailings pond with nearly one third as much entering the tailings pond in a dry year. If one half of this poorer quality runoff could be managed so that delivery to Mildred Lake would be possible a total of 500 hectare meters per year could be subtracted from the inflow; this would amount to nearly one fifth of the estimated surplus in a wet year (column 4 - outflow). Water scheduled for disposal in the tailings pond in a dry year is much less than in a wet year but with good management practices there would be a potential of diverting 100 hectare meters to Mildred Lake rather than to the tailings ponds.

The tailings pond should be minimal in size, thus as little water as possible should be diverted to these ponds. If possible, separation of water into quality classes would be helpful so that water could be used in the highest class possible. As mentioned before, in the early stages of development the greatest possible surface area of pond should be used within the area reserved for pond development. Tailings ponds should be open as early as possible in the spring and kept open as long as possible in the fall. One way of lengthening the ice free season is to change the albedo patterns on the ice surface. Local inflow into the tailings ponds should be kept to a minimum because this relatively cold water would reduce evaporation rates from the tailings pond. Keeping as large a surface as possible open in winter should be a major objective, thus evaporation will be high and heat will not dissipate through the ice without evaporation associated with it. There is a possibility that some of the higher quality water could be used for irrigation of revegetated areas as it

seems quite certain that water deficiencies are going to be a major problem (Syncrude, 1977).

Runoff in the overburden should be kept to a minimum and Laycock (1976) has suggested that in some cases tarpaulins could be used in seasons when potential evapotranspiration is low. This water falling on tarpualins could be of high enough quality for any use. Percolation to the mines should be kept to a minimum, as much of this interflow and shallow ground water flow originating west of the mine site could be avoided. Off site water management alternatives are discussed in section 6.4.

If a goal of reduction in surplus is to be achieved management of the outflow variables would deal mainly with the process of evaporation. Evaporation is the major means available for disposing of tailings effluent, hence unnecessary disposal of water in the tailings ponds should be kept to a minimum. Yearly evaporation from an open water body such as the tailings ponds is highly variable with a net 35 centimeters of water being evaporated in the driest year (Evapotranspiration - precipitation). In a wet year such as 1973 a net gain of 14 centimeters of water (Precipitation-evapotranspiration) would have been added to the tailings ponds. Values for net evaporation for the period 1947 through 1976 are in Appendix IV. Evaporation during 1971, the driest year for the period of record used, would have removed 800 hectare meters of water from the tailings ponds through natural evaporation, while a wet year may provide an additional 325 hectare meters to the ponds. (These estimates were made assuming that the tailings ponds would cover surface area

of 23 square kilometers which should occur in the early 1980's). The limited net natural evaporation illustrates the problems which will arise when management is trying to dispose of these vast quantities of water on the lease site. Extra evaporation will undoubtedly result from the high temperature of the effluent flow released in the tailings ponds. Very little literature is available on the increase in evaporation which could be expected from the increased warmth of water bodies of this size. A general rule to follow would be to keep vapor-pressure gradients as steep as possible. Laycock (1976) suggested that it may be helpful to have one smaller pond with a very steep vapor pressure gradient than a larger pond with warm tailings effluent dispersed throughout. Any means of increasing turbulent transport of air over the ponds would increase evaporation. Artificially induced winds may be helpful with sprinklers added to provide a greater exposed water surface area.

Continental arctic high pressure systems forming in the MacKenzie Valley sometimes stagnate over northern Alberta; these systems are characterized by calm conditions with a low level temperature inversion occurring over large land areas. On a micro-climatic scale a local inversion would occur over the tailings ponds reducing evapotranspiration and increasing ice fog conditions. Artificially induced winds may be helpful in increasing evapotranspiration and managing the direction of ice fog movement.

Runoff estimates (b) and (c) in the inflow section of table 6.1 were based on yields which would have been derived in 1972 (wet year) and 1975 (dry year) using tentative land-use changes expected on the Syncrude

Lease site in the year 1980. The changing water yields estimated are given in table 6.2 and the water balance patterns are all too evident Before development (e.g., 1970) much of the land to be modified was covered by muskeg, aspen and black spruce with soil moisture utilization levels of 10, 15 and 25 centimeters. In most years surpluses were low and soil moisture utilization occurred well into the summer. Surpluses which did occur were caused by snowmelt runoff and early spring rains falling on soils at or near soil moisture capacity levels. Most surpluses derived in late summer were caused by heavy showers with intensities exceeding the infiltration capacity of the soils. Only after a series of wet years (e.g., 1972, 1973) would the higher storage levels have contributed significantly to surpluses. This was the case in 1971 when all storage levels provided high yields. Although muskeg is placed in a high soil moisture storage level discharge relationships are not the same as a well drained close crowned forest with the same soil moisture storage level (for further discussion see section 5.3).

Land use changes relating to development will be evident by 1980, with clearing and preparation for mining changing much of the higher storage levels into surface areas capable of only 1.3 centimeters and 5 centimeters of soil moisture storage. Surplus generated in a dry year (as in 1975 - Stage I) is only one fourth of that generated in a dry year after modification of storage levels (as in 1975 - Stage II). A year typical of average climatic conditions (i.e. 1976) provides a twofold increase in surplus by 1980. Any large local increases in condensation could also provide additional surplus not shown in table 6.2. Total yearly surpluses

under wet year conditions (i.e. 1974) do show significant increases in estimated surplus from stage I to stage II, but as a percentage increase they are not as great as the dry year increases.

Development by the year 2000 A.D. is expected to follow the general trend of an increasing percentage of land area being converted from higher to lower soil moisture storage levels with a related increase in surplus. By stage III in the developmental sequence it is likely that internal drainage areas (10,368 hectares) will provide as much runoff in a wet year as the whole Beaver Creek Basin provided in 1972 (table 5.2). Surpluses are not as variable by stage III, as high yields are produced even in the drier years. If land use changes continue as tentatively planned, over 50 percent of the internal drainage area will have a soil moisture storage capacity of 2.5 centimeters or less. Thus, high surpluses are generated even in the drier years.

Along with these low storage levels much flashier flow can be expected and the potential for erosion is accordingly increased (Hallock, 1976). A change in regime can be related to lowering of soil moisture storage levels; even with storage levels at or near zero a moderate to heavy summer storm can recharge storage and provide some surplus (this was the case in August, 1976). Surpluses can be expected during any month instead of the seasonal pattern typical of higher storage levels. Erosion potential is also increased when land surfaces are raw and exposed. Areas in and around the construction site and the west interception ditch now provide the highest erosion potential. High sediment loads originating in the construction area were observed in the lower reaches of Beaver Creek during

the summer field season.

Discussion has been focussed upon expected water yield and regime patterns within the internal drainage area of Crown Lease 17. Water management objectives for control of inflow and outflow categories in table 6.1 have also been suggested. One management objective not yet discussed, holding future promise, is the modification of precipitation. Since inflow variables (b) and (c) are mainly dependent upon precipitation, any means of reduction would be relevant. Weather modification is still in the primitive stages, thus even marginal control of precipitation is probably in the distant future. Control and management of precipitation, especially snow, is one way of reducing environmental (i.e. polluted water) and operational (i.e. disposal of water) problems.

Management of snow cover in the plant and mining area is one method of significantly altering water balance patterns. Land surfaces capable of receiving 1.3 centimeters of soil moisture storage have had anywhere from 5 to 22 centimeters of snow (i.e. water equivalent) in surplus at the time of spring snowmelt during the period 1945 to 1976.[1] Land surfaces with storage levels of 5 centimeters had anywhere from 1 to 19 centimeters (i.e. water equivalent) of snow in surplus at the time of snowmelt. Average precipitation held in surplus at the time of spring snowmelt were 12 and 9 centimeters for land surfaces capable of 1.3 and 5 centimeters of storage, respectively. Thus, between one fourth and one third of the average yearly precipitation is held in the snow cover ready to fill soil

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[1]All precipitation occurring in months with a mean temperature below 0° centigrade was considered to be snow.

moisture storage levels to field capacity, to add to local ground water flow, and a major portion to runoff as overland flow at the time of spring snowmelt.

The use of snow fences, as a means of collecting snow, is one management tool that can be used to decrease runoff to the tailings ponds. Much of the snow fence research to date has been directed toward the single goal of increasing water yield in alpine areas. Martinelli (1967) used snow fences to increase natural snow accumulation by one half hectare meter of water per 35 meters of snow fence, in the Rocky Mountains. Snow fences have been used on the Great Plains to hold snow on the fields, preventing major accumulations in ditches and shelterbelts. Snow fences have been used throughout the North Central States to prevent snow from blocking rail lines and highways. Woodburn (1977) suggests that snow fences could be used to provide increased yield and help raise lake levels in the Cooking Lake Moraine.

Snow fences provide a relatively simple means of decreasing runoff to the tailings ponds if the fences are placed on land surfaces providing high quality yield. Assuming that snow is collected and runoff is ditched from areas of high quality, these surpluses would reduce flow to the tailings ponds, subsequent increases in yields could be diverted to Mildred Lake. Any surplus diverted from the tailings ponds to Mildred Lake would lessen the water requirement from the Athabasca River, thus reducing the "total" figure on the input side of table 6.1. Placement of snow fences would require visual observation from one winter to the next, as changing land use patterns will change the drifting patterns.

McKay (1970) found that if no major changes in land use occur and winds are repetitive seasonally, the drifts will occur in the same location year after year and will take approximately the same shape. Even before Syncrude's plant becomes operational many areas are known to serve as unwanted collectors of snow. The mine pit will serve as a major artificial landform which will collect a major portion of the snow blowing across it. Any snow settling on the floor of the mine pit will almost assuredly provide low quality surpluses at the time of spring snowmelt. The tailings ponds, coke storage and surge piles are areas that should be kept free of major drift build ups because of the low quality yield provided. Drifts in and around the building areas may provide yield of high enough quality to be disposed of in Mildred Lake.

Three water balance equations are presented in table 6.3 to illustrate

Table 6.3: Water Balance Patterns Associated With Snow Fences (Cm)*

44.0 = (50.0 - 24.0) + 18.0	Average Water Balance.
44.0 - 9.0 = (50.0 - 24.0) + 9.0	Areas from which snow drifted.
44.0 + 9.0 = (50.0 - 24.0) + 27.0	Areas collecting snow near fences.

* A storage level of 5 centimeters was used for all equations.

the effect of the snow fence on the water balance patterns in and around the plant and mining area. In table 6.3 drifted areas and areas from which snow has drifted are equal. Usually they are not as the drifts will

receive snow from 2 or 3 times their area. Thus, water balance patterns from areas collecting snow would contribute more surpluses than are shown in table 6.3. Total surplus remains the same but a greater percentage of yield is generated from a smaller surface area. Localizing the surplus in areas capable of producing high quality yield may then justify ditching to expedite removal of these surpluses to Mildred Lake.

Other on-site means of reducing surpluses do exist. Shelter belts of trees act much like snow fences in that they are snow catch areas. Shelter belts have the added benefit of using local surpluses in the summer generated from adjoining areas of lower soil moisture storage. Planting of trees and shrubs on the plant site could be done so as to complement the final site reclamation plan. Shallow local ponding, both advertent and inadvertent, in the plant and construction areas would help to evaporate shower precipitation. Evaporation over these dark surfaces would occur rapidly. In most areas such as parking lots and roof tops a centimeter or two of water would not be a major inconvenience if slightly ridged walkways were provided. This would also help to reduce the flashy flow from the paved and cleared areas.

6.4 Water Management Alternatives - Off Site

Water management alternatives outside the plant and construction areas could be implemented to benefit future mining operations as well as the environment. Assuming that one of the Syncrude objectives is reduction of local ground water flow to the mine pit, then the fast removal of spring surpluses would probably reduce local ground water flow because

there would be less recharge. Removal of spring surplus does not have to be single purpose in origin; removal of surpluses would assist in the preparation of the area for possible future mining and also increase the very low forest productivity of these saturated muskeg areas. The reduction of local ground water flow and complementary benefits can be done by collecting and concentrating snow for removal by ditching and draining of these collecting areas as well as muskeg areas.

Much of the surficial material west of the plant site consists of organic materials on a relatively level landscape. A current study (Surficial materials map in preparation by Division of the Department of Energy and Natural Resources, Resource Capability Group, Resource Evaluation and Planning, 1977), using the most recent air photos shows organic deposits over much more of the basin than is shown in the preliminary work done by Bayrock (1971). Ozoray (1974) found that extended periods of soil frost coupled with the high clay content of the soil disrupted normal ground water circulation for most of the year and much of the ground water moves in a thin active layer parallel to the surface. The interflow in these organic deposits acts as both recharge to and discharge for local flow systems and as a source of discharge to smaller tributaries within north-eastern Alberta. Stichling and Blackwell (1958) have shown that depressional storage will greatly affect the total volume of runoff in a given year. By reducing this total area in depressional storage less water will be held in storage, thus less will be available as local groundwater flow or interflow.

During the summer field season, visual observation during an extended

dry period showed that Creeks One, Two and Three had a base flow of .03 cubic meters per second or less (i.e. on the order of 1 cubic foot per second) at the outlet on the west interception ditch. As mentioned previously this muskeg drained by Creeks One, Two and Three is capable of having a large percentage of soil moisture locked in dead storage. Throughout dry periods in early and mid summer of 1976 runoff from interflow and muskeg storage was released very slowly to the tributaries of Beaver Creek. If ditching were to take place much of the water held in dead storage would be drained and greater drying of the area would take place, especially during the summer months. In the earlier years following ditching runoff would be flashier and less moisture would be held in the soil for evapotranspiration and ground water recharge. Yield and regime patterns would be altered to respond much like water balance patterns in the 5 centimeter storage level. In later years following ditching increased forest vigor would cause a deeper more extensive root system to develop, thus a change toward higher soil moisture storage levels would occur. This storage change through time would not produce any undesirable patterns.

Management alternatives related to snowpack control and modification in forest areas in the study area should be considered. If the same assumption is made that removal of surplus will reduce local ground water flow then snow can be managed in forested areas west of the interception ditch to meet this objective. Swanson (1972), working in Streeter Experimental Basin in south-western Alberta, found that the forest canopy can be manipulated to alter snow accumulation patterns. Snow accumulations in the forest openings ran approximately one-third greater than accumulations

in adjacent aspen stands. MacKay (1970) found that forest meadows act as snow traps and accumulation of snow is greater than in the surrounding forest. A series of clearings in the forest stands, if supplemented with the proposed ditching, could be used to remove spring surplus thereby reducing water available for groundwater recharge. Reduction of moisture held in the muskeg as well as removal of spring surplus might possibly stimulate forest growth which in turn would increase evapotranspiration rates. This forest clearing is complementary to clearing which will be required if mining is to take place in the future.

Increased accumulation of snow can be expected along the edge of the forest and here again ditching would be beneficial for removal of this surplus. The forest edge acts much like a wall or snow fence and where ever winds decrease, snow is deposited from the air. These build ups of snow banks extend into and out of the forest for a distance on the order of five times the height of the trees. (Kazman is used in MacKay, 1970). In a study conducted in the Cooking Lake Moraine (approximately 480 kilometers south of the study area) Witter (1976), using density slicing techniques showed an increase in snow accumulation along the forest margin. High quality yield from the forest margin could be ditched into Mildred Lake, thus reducing water need from the Athabasca River. If government regulations change and off site disposal is permitted Syncrude has two major water management alternatives to choose from; first, water supply can be derived from both the Athabasca River and local surpluses diverted to Mildred Lake; second, all water supply can be derived from the Athabasca with disposal of high quality surpluses into the river via

the west interception ditch. Either alternative mentioned can be adopted to reduce the input side of table 6.1, whether it be by reduced pumping from the Athabasca River or disposal of surpluses from the lease site.

6.5 Water Management Alternatives - Thickwood Hills

Beaver Creek drains approximately 16,000 hectares of land south of the Syncrude site, with the headwaters in the Thickwood Hills. Flow from this upland area is being diverted from the Beaver Creek drainage system over a low divide into Poplar Creek Reservoir. No major land use changes have taken place and forest growth has remained unchanged since settlement of the region except for clearing of cut lines in the area. Recreational activities such as snowmobiling, hunting and cross-country skiing are the only (very limited) uses by man. These recreational activities are limited to areas along and near the road leading from Fort McMurray to Thickwood Hills Lookout. These uses have had little effect on the water balance in the headwater area of Beaver Creek.

No major land use changes have been planned for this area of the drainage basin, as the depth of overburden to mineable oil sand is too great to justify surface mining at this time. Regime and yield patterns should remain much the same as they have in the past. The discharge from the Thickwood Hills is greater per unit area than from areas 200 meters lower, such as areas in and west of the mining and plant site. Although total yield from this area is less than from the original Beaver Creek, yield per unit area is greater from the uplands. Runoff regime from the upland areas is different than that of Creeks One, Two and Three which

originate west of the Syncrude site. Spring snowmelt begins late in the upland areas, as temperatures are cooler. A spring snowmelt hydrograph would show less peaking than that of tributaries in lower reaches of the basin as snowmelt in upland areas would have a longer duration. Soil moisture storage is recharged to higher levels in spring and it remains somewhat higher than in the lower reaches of the basin because of reduced spring and summer potential evapotranspiration.

One future objective of Syncrude may be to increase or control surpluses to help flush saline waters from mine depressurization which are being disposed of into the Beaver Creek Reservoir. Many alternatives could be used to increase yields from the headwaters of Beaver Creek; those previously mentioned such as ditching, snow collecting and snow pack management would apply as well. Increased yields could be obtained by forest clearing procedures while still maintaining water quality. Colman (1948) and Satterland and Eschner (1965) provide background material on the effects of forest clearing on yield. Yield and regime patterns from the upland areas are important not only for planning and scheduling of saline water disposal but also for future use and construction of a new drainage channel to be developed after mining ceases. A more detailed discussion of these patterns can be found in the work done by Waddell (1977).

Water management alternatives presented in this chapter have been based upon current government regulations and Syncrude's future plans (Syncrude personnel, 1976 & 1977). After analysing the water balance patterns, the author presented water management alternatives based on the

finding that future yields will be greater than has been indicated in Syncrude reports to date and on-site disposal problems will occur. All surpluses derived should be of the highest quality possible. All water management objectives should be directed in part toward reducing inputs and increasing outputs outlined in table 6.1. If Great Canadain Oil Sands and Syncrude are only the first in a series of oil sand extraction plants, then results of water management decisions, whether they proved useful or not, should be examined with the objective of improving later developments. Management alternatives and yield predictions were based on published material from government and private sources as well as Syncrude studies. Changes in technology, both in bitumen separation and removal of tailings "fines" could greatly alter expected water balance patterns during the "life" of the Syncrude operation. Water management alternatives will have to be made flexible so adjustments can be made to meet changing objectives. Both Syncrude and government officials must realize that problems arising from ditching, clearing of land and disposal of water cannot be limited by something as artificial as a lease boundary or an interception ditch. Therefore, all people involved in making water management decisions must consider the dynamic applications of the hydrologic cycle.

CHAPTER VII

Summary Conclusions Recommendations

7.1 Summary

The major objectives dealt with in the thesis are: 1) identifying water balance patterns in Beaver Creek Basin; 2) gaining an understanding of the interaction of the component parts of this balance in each part of the region; 3) applying these water balance patterns so that potential water related problems can be avoided and opportunities for better water management may be developed. Knowledge of these overall patterns is vital to Syncrude planners responsible for reclamation programs and the re-establishment of future drainage patterns for Beaver Creek. If construction of additional oil sands extraction plants occurs, an understanding of local regime and yield patterns will be necessary for determining water supply and disposal needs which can be expected at the regional level. Thus, baseline data of the more local regime and yield patterns is necessary before the regional patterns may be understood.

The regional hydrology of north-eastern Alberta is discussed in chapter III to give the reader some perspectives of regime and yield patterns which occur within the region. Discharge recorded on the Ponton and Boyer Rivers is presented in table 3.1 to show the much larger yields which are generated from upland streams. Much of the yield generated in northern Alberta originates in these upland areas (e.g., Stony Mountain, Thickwood Hills, Birch and Caribou Mountains). A discussion of the different yearly patterns of hydrographs of Beaver Creek is included in

section 3.4 for a better understanding of regime patterns in the study area.

The water balance patterns are examined using two broad classes; the internal or modified land including all surface drainage to the tailings ponds and Mildred Lake and the external water balance patterns which include all other surface areas drained by the existing Beaver Creek Channel and the tributaries now diverted by the interception ditch. These water balance patterns are examined as they vary both spatially and temporally (both from season to season and year to year). The water balance procedures as developed and modified by C.W. Thornthwaite (1948, 1955, 1957) are used in an attempt to better define the water regime and yield relationships of Beaver Creek Basin. As a check of the reliability of the procedures, 5 years of yearly discharge records are used to check estimated surpluses with gauged runoff (Environment Canada, 1972-1975). Interviews and discussions with Syncrude personnel and people living and working in the area were helpful in providing a better understanding of water regime and yield relationship's which have occurred in the past field season and in previous seasons.

A literature search was conducted in an effort to determine the results obtained and conditions (i.e. soils, vegetation and climate) of studies using water balance procedures in North America, and especially western Canada. Some of these studies involved estimating potential evapotranspiration while others focussed upon consumptive use of water by agricultural crops. The literature search was also used as a means of determining where the largest errors tend to occur and corrections

needed to be made in water balance procedures. To date Thornthwaite's method for estimating potential evapotranspiration has been the major method used in establishing water balance patterns, in the study area. Penman's method for estimating potential evapotranspiration is compared with that of Thornthwaite's and the results are summarized in table 4.3.

In chapter V the overall water balance patterns which have prevailed in the early 1970's are discussed. Basin yield data are presented for the period 1972 through 1976 with a discussion of these yields. A summary of water balance patterns using daily procedures is included (tables 5.1 through 5.6) with a discussion of the differences in results between monthly and daily water balance procedures. Yield differences from within the study area are also discussed.

Estimates of future water regime and yield patterns expected in two developmental sequences (i.e. 1980 and 2000) are presented in table 6.1. Discussion focusses upon the yearly yield patterns which may occur and the change in runoff regime which may be expected. A host of water management alternatives are presented which would alter expected yield and regime patterns, if implemented, both in modified land areas as well as in areas west and south of the present construction and mining site. Although many problems and hazards are identified, many of these water management alternatives would be complementary to desired water balance changes and would provide environmental enhancement benefits in the study area.

7.2 Conclusions

Before water balance procedures could be employed a decision had to be made concerning the method to be used for estimating potential evapotranspiration. A number of procedures were reviewed and the two most promising, both of which had been used in Alberta, were applied in this study. Penman's method for estimating potential evapotranspiration is compared with that of Thornthwaite's and the results are summarized in table 4.3. If a scaling factor is not used, use of Penman's method results in serious underestimates of potential evapotranspiration. Three drawbacks of the Penman method are apparent: Firstly, many of the specific data needed for the computation are not available from Mildred Lake or even Fort McMurray so interpolation of data is necessary; secondly, since solar radiation is the controlling variable in the equation, potential evapotranspiration is almost nil from October through April when a limited amount of potential evapotranspiration occurs, and temperature, wind, and humidity play a minor role in the equation; and thirdly, estimates of potential evapotranspiration are too low if compared to precipitation and gauged surplus so a scaling factor would be required to provide reliable results in what many researchers call an analytical equation.

In a review of the literature, the author found that the Thornthwaite water balance procedures had been the most widely used in western Canada and had yielded reasonable results. Surplus estimates made using Thornthwaite procedures were within ± 10 percent of gauged runoff for the three year period 1972 through 1974 but a poor relationship exists between

estimated and gauged surplus in the drier years, 1973 and 1976 (tables 5.7) Part of the underestimation in these years can be attributed to the lower potential evapotranspiration and higher precipitation in the Thickwood Hills. Soil moisture carryover from the wet years of 1973 and 1974 was greater in the Thickwood Hills than in the lower reaches of Beaver Creek Basin, thus greater surpluses were generated in the uplands.

A major source of error in the use of the water balance procedures in northern Alberta is caused by impeded rates of evapotranspiration caused by the insulating blanket of largely dead organic material upon muskeg surfaces. This source of error is strikingly evident in the peak of the discharge hydrograph of 1976 (Figure 3.4). Almost 6 centimeters of rain were recorded from August 25th through the 28th and prior soil moisture storage was at zero in all but the 25 centimeter storage category yet approximately two-thirds of this precipitation was recorded as discharge. Actual evapotranspiration in muskegs is apparently well below the potential rate even though water is not a limiting factor. This insulating mat seriously restricts the air movement over the water surface thus reducing the vapor pressure gradient. Too much water in the soil impedes growth rates of vegetation thereby reducing transpiration rates. The insulating mat may also contribute to slow melting of frost in the soil, thus cold water in the root zone may limit growth. Therefore, although these forest soils have 15 to 25 centimeter soil moisture capacities they are effectively acting much like a 5 centimeter soil moisture storage level because of the "dead" or less than fully utilized storage.

Greater yields can be expected from the Thickwood Hills as well as other upland areas in northern Alberta. Hallock (1976), in a study in the Gregoire Lake Basin just south of Fort McMurray, has shown that greater yields can be expected from Stony Mountain Plateau than in the lowland. Yearly discharge data from the Ponton and Boyer Rivers support this expected increase in yield (table 3.1). A comparison of summer precipitation data between Fort McMurray and Thickwood Hills showed that a 15 to 20 percent increase in precipitation can be expected in the uplands along with a decrease in potential evapotranspiration of nearly 5 centimeters. An adjusted water balance representative of the patterns existing in the uplands of the study area is shown in table 4.5 and one striking difference is that of surplus estimates. Using average year temperature and precipitation data the calculated surpluses generated in the uplands amount to 16 centimeters or nearly 3 times the surpluses generated in the lowlands.

One of the major objectives was to estimate future yield and regime patterns in Beaver Creek Basin using future land use plans so that water related problems could be identified and avoided. Knowledge of future water balance patterns may provide opportunities for management decisions which are advantageous in both environmental enhancement and Syncrude's operation. Greater surpluses can be expected from land surfaces which have been modified (i.e. operations and mining areas) than from the natural forested lands. Estimates of runoff to the tailings ponds (b) and Mildred Lake (c), on the inflow side of table 6.1 were based on yields in 1972 (i.e. a wet year) and 1975 (i.e. a dry year) using

tentative land-use patterns expected on the Syncrude site by the year 1980. Before development (i.e. 1970) much of the land to be modified was covered with muskeg, aspen and black spruce, thus having relatively high soil moisture storage capacities. Much of the total yearly surpluses which did occur were caused by snowmelt runoff and early spring rains. Total yearly surpluses from modified areas will greatly increase Surpluses generated in a dry year are four times greater after modification of soil moisture storage levels than before modification (as in 1975 - Stages I & III). If water balance patterns similar to 1976 occur in 1980 a twofold increase in surplus can be expected from modified surface areas. Total yearly surpluses under wet year conditions will also increase but as a percentage increase they are not as great as the dry year increases. Thus, most years will provide relatively high surpluses in later stages of the mining operation and much of the variability from year to year will not occur.

A change in land-use resulting in lower soil moisture storage capacities will alter the runoff regime and increase the potential for erosion. Surpluses can be expected in all years from snowmelt runoff alone and even with soil moisture storage capacities at zero, moderate to heavy rains will completely recharge soil moisture and produce some surplus. Raw and exposed surfaces in and around the construction and mining site and along the west interception ditch provide the highest erosion potential. Flashier flow can be expected as less surface detention storage is provided for the much larger runoff.

Finally, daily water balance patterns were found to be a much better

indicator of the actual water balance patterns than the monthly computations. In the comparatively wetter years such as the early 1970's monthly patterns provided estimates of surplus and deficiency patterns close to those using daily estimates. Daily water balance procedures were shown to be far superior to monthly procedures, especially in the drier years and years when precipitation was unevenly distributed. This refinement in procedures is most desirable but others such as the modulated budget which allows for the decreasing rate of soil moisture withdrawal as the wilting point is approached, using 50% detention storage from month to month to account for basin lags in runoff calculations, and other adjustments and refinements could have been employed. Many of these refinements are of limited value and are sometimes inappropriate in the study area. A refinement to account for actual evapotranspiration being less than potential evapotranspiration in muskeg areas is needed but additional studies are necessary.

7.3 Recommendations

The author would strongly recommend that a day to day water balance study be initiated so that water balance relationships can be monitored and any changes which take place in yield and regime patterns would not come wholly unexpected. A daily water balance would be a first step in developing a continuing forecast base which could serve as an indicator of expected surplus and deficiency patterns. Estimations of spring surpluses can be made in late winter and decisions concerning use or disposal of these surpluses can be made in an effort to improve plant

operations. Revegetated areas will have very low soil moisture storage levels because of the "soil" and shallow depth of rooting and unless irrigation scheduling is planned revegetated areas will suffer from drought by late June in most years. A monthly water balance could not provide the day to day information which will be needed by Syncrude planners.

The expected size of the tailings ponds has increased from 2.5 square kilometers in 1962 to over 30 square kilometers in the early 1970's, thus any water management decisions should be aimed, at least partially, in keeping inflow to a minimum and outflow to a maximum. It may prove beneficial if future studies were conducted in an effort to determine the optimal evaporation patterns obtainable by controlling vapor-pressure gradients. Studies on different methods of increasing natural evaporation may also prove beneficial. Further research on centrifuging and chemically induced settling would be helpful as they provide much faster settling rates of sand fines allowing a greater percentage of water to be reused.

A number of water management alternatives which can be used to control inflow to the tailings ponds and Mildred Lake are presented in chapter VI. Further study of operations and mining area alternatives would be desirable before implementation. Management and control of snow cover in the plant and mining area would allow for relatively easy management of nearly one-third of the yearly precipitation. Presently some areas are known to be unwanted collectors of snow such as the mine pit, coke storage, and surge piles. Other areas which would yield low

quality surplus should be identified as operations begin so that measures can be taken to prevent drifting into these areas.

Concentrating snow and ditching in the forested area west of the construction site is one method of providing three major benefits: firstly, reduction of local ground water flow to the mine pit; secondly, ditching and drainage will help prepare the area for future mining; and thirdly, drainage will stimulate forest productivity and increase use by wildlife. It will be necessary to determine the origin of local ground water flow to the mine pit before the flow can be reduced. Ditching and drainage should be used to remove water held in dead storage by the muskeg. This ditching and drainage will remove excess surpluses and indirectly increase transpiration rates by increasing vigor of the vegetation. It may be desirable to review the work done on drainage of peatlands in Northern Europe (e.g., Mustonen in Finland) as they have used drainage for increasing forest productivity.

If future oil sands operations are constructed it will be necessary to define water balance patterns which occur over a much larger area than that of Beaver Creek Basin, if knowledgeable decisions are to be made for proper management of this renewable resource. On the regional level two areas need future research. Firstly, a better understanding of the variation in precipitation patterns between uplands and lowlands are needed so that more accurate estimates of water balance patterns can be made. Secondly, and most importantly further research on actual evapotranspiration patterns in muskeg areas is needed as this provided the greatest error in the water balance procedures. It would be useful for Syncrude

as well as others interested in water balance patterns if a relationship between potential and actual evapotranspiration were determined. Until this problem is resolved it will be difficult to accurately estimate surpluses in Beaver Creek Basin in the drier years.

In the thesis much emphasis is placed on potential water related problems expected under future plans using the best technology available. Little credit has been given to Syncrude for the construction of dams, dykes and other features which should significantly reduce pollution problems on Poplar Creek, the Athabasca River and areas farther downstream. Many millions of dollars have been spent to stop pollution at the "factory fence" by Syncrude at the expense of mining and operation efficiency. The framework (e.g., the construction features) for drainage during the "life" of the Syncrude operation has been built and now water management objectives must be more closely defined. It is the author's conviction that with flexibility and communication between the public, government and Syncrude personnel water regime and yield patterns as well as water management alternatives can be used as a model for better use of water as a natural resource.

BIBLIOGRAPHY

Alberta Energy and Natural Resources, aerial photography of study area. 1951, 1967.

Alberta Environment, An Environmental Study of the Athabasca Tar Sands. Edmonton: Alberta Environment, 1973, 112p.

Alberta Oil Sands Facts and Figures. Edmonton: Department of Mines and Minerals, 1974, 37p.

Anderson, H.W., "Forest Cover Effects on Snowpack Accumulation and Melt", Central Sierra Snow Laboratory. Trans. Am. Geophys. Union, Vol. 37, 1956, pp.307-312.

Atlas of Alberta, and Alberta Department of Environment, University of Alberta Press, 1969, 157p.

Baker, D.G., A Comparison of Two Evapotranspiration Calculation Methods and the Application of One to Determine some Climatic Differences between Great Soil Groups of Minnesota. Ph.D. dissertation, University of Minnesota, 1962.

Barry, R.G. and Chorley, R.S., Atmosphere, Weather, and Climate. New York: Holt, Rinehart and Winston, 1970, 320p.

Bayrock, L.A., Surficial Geology - Waterways. Preliminary work in 1971, Edmonton: Alberta Research Council, 1975.

Bentley, C.F.; Peters, T.W.; Henning, A.M.F.; and Walker, D.R., Gray Wooded Soils and Their Management. Edmonton: University of Alberta Extension, 1971, 89p.

Blaney, H.F., and Criddle, W.D., "Determining Water Requirement in Irrigated Areas from Climatological and Irrigation Data". U.S. Department of Agriculture, 1950, 96p.

Blaney, H.F., "Definition Methods and Research Data", (a symposium on the consumptive use of water), Trans, Am. Soc. Civ. Engrs. Vol. 117, Paper 2524, 1952, pp.949-967.

Brown, R.J.E., The Distribution of Permafrost and Its Relation to Air Temperature in Canada and the U.S.S.R. Ottawa: National Research Council, 1960, 14p.

Brown, R.J.E., Ground Surface Energy Exchange Studies at Norman Wells, N.W.T. Ottawa: National Research Council, 1965, 36p.

Bruce, J.P. and Clark, R.H., Introduction to Hydro-meteorology. Toronto: Pergamon, 1966, 319p.

Budyko, M.I., The Heat Balance of the Earth's Surface. (English Translation: Stepanova). Washington: office of Technical Services, U.S. Department of Commerce, 1958.

Budyko, M.I., Climate and Life. (English edition edited by D.H. Miller). International Geophysics Series, 18. New York: Academic Press, 1974, 508p.

Canada Transport Ministry - Canada Meteorological Service, Wind Roses of Western and Northern Canada. (Prepared by: Weather Office, International Airport, Edmonton, Alberta. No date.), 157p.

Carrigy, M.A., Geology of the McMurray Formation. Edmonton: Research Council of Alberta, 1959, 130p.

Carrigy, M.A. ed., Athabasca Oil Sands. (The K.A. Clark Volume) Edmonton: Research Council of Alberta, 1963, 241p.

Carrigy, M.A. and Kramers, J.W., Guide to the Athabasca Oil Sands Area. Edmonton: Alberta Research Council, 1973, 213p.

Chalmers, J.W., ed., The Land of Peter Pond. Edmonton: Boreal Institute for Northern Studies, 1974, 131p.

Chang, Jen-Hu, Climate and Agriculture. Chicago: Aldine Publishing Company, 1974, 304p.

Chow, Ven Te, Handbook of Applied Hydrology. New York: McGraw-Hill, 1964, 1452p.

Colman, E.A., "Soil Surveying on Wildlands: The Problem and One Solution", Journal of Forestry, Vol. 46, No. 10, 1948, pp.755-762.

Colman, E.A., Vegetation and Watershed Management. New York: The Ronald Press Company, 1953, 412p.

Critchfield, H.J., General Climatology. Englewood Cliffs New Jersey: Prentice Hall Publishing, 1966, 420p.

Crown, P.H., and Twardy, A.G., Soils of the Fort McMurray Region, Alberta (Townships 88-89, Ranges 8-11) and Their Relation to Agricultural and Urban Development. Alberta Institute of Pedology, University of Alberta, Contribution M-70-2, 1970.

Decker, W.L., "Precision of Estimates of Evapotranspiration in Missouri Climate", Agronomy Journal, Vol. 54, 1962, pp.529-531.

Dingman, S.L., "Characteristics of Summer Runoff from a Small Watershed in Central Alaska", Water Resources Research, Vol. 2, no.4, 1966, pp.751-754.

Eagleman, J.R., and Decker, W.L., "The Role of Soil Moisture in Evapotranspiration", Agronomy Journal, Vol. 57, 1965, pp.626-629.

Environment Canada, Historical Streamflow Summary - Alberta to 1973. Ottawa: Information Canada, 1974, 327p.

Environment Canada, "Monthly Record of Meteorological Data", (1940-1977), Ottawa: Atmospheric Environment Services.

Erxleben, J.P., Land Use - Snowmelt Relationships in the Whitemud Creek Basin. M.Sc. thesis, Department of Geography, University of Alberta, 1972, 178p.

Farvolden, R.N.: Meneley, W.A.; LeBreton, E.G.; and Lennox, D.H., "Early Contributions to Ground Water Hydrology of Alberta", Research Council of Alberta: Bulletin No. 12, 1963, 123p.

Foley, G., The Energy Question. London, 1976, p.343.

Gorrell, H.A., Regional Hydrogeological Study - McMurray Oil Sands Area, Alberta - Phase I. Prepared for: The Oil Sands Environmental Study Group, 1974.

Gray, D.M., "Snow Hydrology of the Prairie Environment", in Snow Hydrology. (proceedings of workshop seminar prepared by the Canadian National Committee), Ottawa: Queen's Printer, 1968, 82p.

Gray, D.M., ed., Handbook on the Principles of Hydrology. (A Water Information Center Publication), Published by the Secretariat, Canadian National Committee for the International Hydrological Decade, 1970.

Gray, D.M., and O'Neill, A.D.J., "Application of the Energy Budget for Predicting Snowmelt Runoff", in Advanced Concepts and Techniques in the Study of Snow and Ice Resources. 1973, pp.108-118.

Hallock, M.C., Water Problems in In-Situ Oilsands Development - The Water Resources of the Gregoire Lake Basin. M.Sc. thesis, Department of Geography, University of Alberta, 1976, 169p.

Hardy, W.G. (Editor-in-Chief), Alberta: A Natural History. Edmonton: Hurtig Publishers, 1967, 343p.

Hare, F.K., and Hay, J.E., "Anomalies in the Large-Scale Annual Water Balance over Northern North America", Canadian Geographer, Vol. 15, No. 2, pp.79-94, 1971.

Hare, F.K., "The Observed Water Balance of North America", in International Geography (edited by Adams, W.P., and Helleiner, F.M.), pp. 147-148, 1972.

Hare, F.K. and Thomas, M.K., Climate Canada. Toronto: Wiley Publishers, 1974, 256p.

Haupt, H.F., "Relation of Wind Exposure and Forest Cutting to Changes in Snow Accumulation", in International Symposia on the Role of Snow and Ice in Hydrology. Banff, Alberta, 1972, 11p.

Hibbert, A.R., "Forest Treatment Effects on Water Yield", in International Symposium on Forest Hydrology. (Edited by Sopper, W.E., and Lull, H.L.) Pergamon Press, 1967, 527-543p.

Hobbs, E.H., and Krogman, K.K., "A Comparison of Measured and Calculated Evapotranspiration for Alfalfa in Southern Alberta", Canadian Agricultural Engineering, Vol. 8, pp.9-11, 1966.

Hobbs, E.H., and Krogman, K.K., "Observed and Estimated Evapotranspiration in Southern Alberta", Transactions of the American Society of Agricultural Engineers, Vol. 11, No. 4, pp.502-507, 1968.

Holton, H.N., in Handbook for Applied Hydrology. Edited by Chow, Ven, Te, Section 12, "Infiltration", McGraw-Hill, 1964.

Hornbeck, James W., "Streamflow Response to Forest Cutting and Revegetation", Water Resources Bulletin, American Water Resources Association. Minneapolis: December, 1975, 5p.

Hoyt, W.G., in Rainfall and Runoff (by Forster, E.E.). New York: The MacMillan Company, 1949, 487p.

Kakela, P.J., Snow and the Thornthwaite Water Balance in a Subarctic Environment, University of Alberta, 1969, 289p.

Kakela, P., "Thornthwaite's Climatic Water Balance: Evaluation of Annual Discharge Estimates for Two Subarctic Basins", Canadian Geographer, Vol. 27, No. 2, pp.167-179, 1973.

Kazmann, R.G., Modern Hydrology. New York: Harper and Row, 1965.

Kellerhals, R.; Neill, C.R.; and Gray, C.I., Hydraulic and Geomorphic Characteristics of Rivers in Alberta. Edmonton: Alberta Research Council, 1972, 52p.

Kellerhals, R., Preliminary Hydrological Investigation of Crown Lease No. 17 in the Athabasca Tar Sands. (prepared for Syncrude Canada Ltd.) By L.G.L. Ltd. Environmental Research Associates, 1973, 54p.

Kittredge, J., Forest Influences. New York: McGraw Hill Book Company, 1948.

Landals, A.G., Snowmelt Runoff-Yellowknife, N.W.T. M.Sc. thesis, Department of Geography, University of Alberta, 1970, 115p.

LaRoi, G.H., "Taiga", in Alberta a Natural History, (editor-in-chief - Hardy, W.G.). Edmonton: Hurtig Publishers 1967, pp.151-169.

Laycock, A.H., "Lake Level Fluctuation and Climatic Variation in Central Canada", Proceedings: Symposium on the Lakes of Western Canada. Edmonton: University of Alberta Water Resources Center, 1971, 13p.

Laycock, A.H., "Precipitation and Streamflow in the Mountain and Foothill Regions of the Saskatchewan River Basin". Regina: Prairie Provinces Water Board Report No. 6, 1957, 48p.

Laycock, A.H., "Drought Patterns in the Canadian Prairies" in Proceedings: Helsinki Congress of the International Association of Scientific Hydrology. Publication No. 51. Louvain: August, 1960, 13p.

Laycock, A.H., Water Deficiency Patterns in the Prairie Provinces. Regina: Prairie Provinces Water Board, 1964, 50p.

Laycock, A.H., Water Deficiency and Surplus Patterns in the Prairie Provinces. Regina: Prairie Provinces Water Board, Report No. 13, 1967, 92p.

Laycock, A.H., "Forecast of a Very High Spring Runoff in 1974", Presentation to Renewable Resources Sub-Committee, Public Advisory Committee to the Environment Conservation Authority. (Xerox Copy), 1974, 14p.

Laycock, A.H., "Water Problems in Alberta Oilsands Development", Proceedings: Symposium on Water Resources Problems Related to Mining. Minneapolis: American Water Resources Association, 1974, 16p.

Laycock, A.H., "Water Balance Studies in Syncrude Operations", Unpublished research proposal, March, 1976, 21p.

Lettau, H., "Evapotranspiration Climatonomy: A new approach to numerical prediction of monthly evapotranspiration, runoff, and soil moisture storage", Monthly Weather Review. Vol. 96, 1969, pp.691-699.

Lindsay, J.; Heringa, P; Pawluk, S.; and Odysky, W., Exploratory Soil Survey of Alberta Map Sheets 84C (east half), 84B, 84A, and 74D.

Research Council of Alberta, Preliminary Soil Survey Report 58-1, 1958.

Lindsay, J.; Pawluk, S; and Odynsky, W., Exploratory Soil Survey of Alberta Map Sheets 74M, 74L, 74E, and 73L (north half). Research Council of Alberta, Preliminary Soil Survey Report 63-1, 1963.

Lindsay, J.D., and Odynsky, W., "Permafrost in Organic Soils of Northern Alberta", Canadian Journal of Soil Science. Vol. 45, 1965, pp.264-269.

Longley, R.W., "Climatic Maps for Alberta", Edmonton: Research Council of Alberta and the Alberta Climatological Committee, July, 1968, 8p.

Longley, R.W., Climate of the Prairie Provinces. Toronto: Climatological Studies no. 13, 1972, 79p.

MacFarlane, I.C., Guide to a Field Description of Muskeg, (Based on the Radforth Classification System). National Research Council, Technical Memorandum 44, Ottawa: 1958, p.35.

MacIver, Ian, "Land and Water Resources of the Spring Creek Basin", unpublished masters thesis in Geography, University of Alberta, 1966, 202p.

MacKay, D.K., "Characteristics of River Discharge and Runoff in Canada", Geographical Bulletin, Vol. 8, No. 3, pp.219-227, 1966.

Marchek, Jerry, Environmental Co-Ordinator on the Syncrude Site. Personal communication. Mildred Lake, Alberta, June, 1976 - April, 1977.

Martinella, N., "Possibilities of Snowpack Management in Alpine Areas", in International Symposium of Forest Hydrology. (Edited by Sopper, W.E., and Lull, H.L.) Pergamon Press, 1967, pp.225-233.

McKay, G.A., "Problems of Measuring and Evaluating Snowcover", in Snow Hydrology. (proceedings of workshop seminar prepared by Canadian National Committee), Ottawa: Queen's Printer, 1968, 82p.

Moss, E.H., "The Vegetation of Alberta", The Botanical Review. Vol. 21, No. 9, 1955, pp.493-567.

Muller, R.A., "The Effects of Reforestation on Water Yield", Publications in Climatology. Laboratory of Climatology, Vol. XIX, No. 3, 1966.

Muller, R.A., "Application of Thornthwaite Water Balance Components for Regional Environmental Inventory", in International Geography 1972 (edited by Adams, W.P., and Helleiner, F.M.). Toronto: 1972, 694p.

Muller, R.A., "Comparative Climatic Analysis of Lower Mississippi River Floods: 1927, 1973, and 1975", Water Resources Bulletin, Vol. 12,

No. 6, 1976, pp.1141-1150.

Mustonen, S.E., Water Balance Transformation of Meliorated Areas. Proceedings of a Symposium organized by the IGU - Commission on the IHP, 3rd report, Leningrad: July 19-26, 1976, pp.53-60.

Neill, C.R.; Gray, D. I.; Schouten, M.F.; and Card, J.R., Selected Characteristics of Streamflow in Alberta. Edmonton: Alberta Research Council, 1970, 54p.

Northwest Hydraulic Consultants Ltd., A Preliminary Investigation of Minimum Flows of Selected Rivers in the North-east Alberta Region. Prepared for Ekistic Design Consultants Ltd., Edmonton, 1975.

Northwest Hydraulic Consultants Ltd., Hydrological Aspects of River Basins in the North-eastern Alberta Region. Prepared for Ekistic Design Consultants Ltd., Edmonton, 1975.

Northwest Hydraulic Consultants Ltd., Working Paper on Probable Hydrological Impact of Oil Sands Development. Prepared for Ekistic Design Consultants Ltd., Edmonton, 1976, 26p.

Ozoray, G.F., Hydrogeology of the Waterways - Winnefred Lake Area, Alberta. Edmonton: Alberta Research Council, 1974, 18p.

Pelton, W.L., and Kowen, H.C., "Evapotranspiration Estimates in a Semi Arid Climate", Canadian Agricultural Engineering, Vol. 11, No. 2, 1969, pp.50-53.

Penman, H.L., Natural Evaporation from Open Water, Bare Soil and Grass. Proceedings: Royal Society, Series A, 193, 1948, pp.120-145.

Penman, H.L., "Evaporation: An Introductory Survey", Netherlands Journal of Agricultural Science, Vol. 4, 1956, pp.9-29.

Penman, H.L., Vegetation and Hydrology, Bucks, England: Commonwealth Agricultural Bureaux, 1963, 124p.

Pratt, Larry, The Tar Sands. Edmonton: Hurtig, 1976, 197p.

Prusak, W., Climatologist - Edmonton International Airport. Personal communication, March, 1977.

Sanderson, M.E., "Drought in the Canadian North-west", Geographical Review, Vol. 38, No. 2, 1948, pp.289-299.

Sanderson, M.E., and Phillips, D.W., Average Annual Water Surplus in Canada. Toronto: Climatological Studies no. 9, 1967, 76p.

Satterland, D.R., and Haupt, H.F., "Vegetation Management to Control Snow Accumulation and Melt in the Northern Rocky Mountains", in Watersheds in Transition. (an AWRA Symposium) Fort Collins, Colorado, 1972, pp.200-205.

Satterland, D.R., and Eschner, "Land Use, Snow and Streamflow Regime in Central New York", Water Resources Research, Vol. 1, No. 3, 1965, pp.397-405.

Sharp, P.H.; Birdsall, D.A.; and Richardson, W.J., Inventory Studies of Birds On and Near Crown Lease Number 17, Athabasca Tar Sands. (Prepared for Syncrude Canada Ltd.) Edmonton: 1974, 168p.

Shelford, Richard, (Resource Capability Group, Resource Evaluation and Planning Division, Department of Energy and Natural Resources). Personal communication, November - April, 1976-77.

Sommer, A., and Spence, E.S., "Some Runoff Patterns in a Permafrost Area of Northern Canada", Albertan Geographer, Vol. 4, pp.60-64, 1968.

Stichling, W., and Blackwell, S.R., "Drainage Area as a Hydrologic Factor on the Glaciated Prairies", in International Association of Scientific Hydrology General Assembly. Toronto: Publication No. 45, 1958, pp.365-376.

Strahler, A.N., Physical Geography (fourth edition) New York: John Wiley and Sons, 1975.

Swanson, R.H., "Small Openings in Poplar Forest Increase Snow Accmulation", in International Symposia on the Role of Snow and Ice in Hydrology. Banff, Alberta, 1972, 9p.

Syncrude Canada Ltd., Environmental Impact Assessment. 4 Vol.: 1 Overview; 2 Consideration of Resource Development Alternatives; 3 Base Line Information; 4 Supporting Studies, Edmonton, 1973.

Syncrude Canada Ltd., The Habitat of Syncrude Tar Sands Lease #17: an initial evaluation. Edmonton: 1973, 40p.

Syncrude Canada Ltd., Migratory Waterfowl and the Syncrude Tar Sands Lease: A Report. Edmonton: 1973, 67p.

Syncrude Canada Ltd., The Hydrology of Lease 17: a report of studies completed in the year 1973. Edmonton: 1974, 44p.

Syncrude Canada Ltd., Revegetation: species selection - an initial report. Edmonton: 1974, 47p.

Syncrude Canada Ltd., Baseline Environmental Studies of Ruth Lake and

Poplar Creek. Edmonton, 1975, 118p.

Syncrude Canada Ltd., Proposal for the Disposal of Basal Aquifer Saline Water to the Surface Water System from 1976 to 1980. March 7, 1975, 44p.

Takyi, S.I.; Rowell, M.H.; McGill, W.G.; and Myborg M., Reclamation and Vegetation of Surface Mined Areas of the Athabasca Tar Sands. (Prepared for Syncrude Canada Ltd.) Edmonton: 1977, 170p.

Thornthwaite, C.W., "An Approach Toward a Rational Classification of Climate", Geographical Review, Vol. 38, No. 1, 1948, pp.55-94.

Thornthwaite, C.W., and Hare, F.K., "The Loss of Water to the Air", Agricultural Meteorology - American Meteorological Society. Meteorological Monographs, Vol. 6, No. 28, pp.163-180.

Thornthwaite, C.W. and Mather, J.R., "The Water Balance", Publications in Climatology. Laboratory of Climatology, Vol. VIII, No. 1, 1955, 104p.

Thornthwaite, C.W., and Mather, J.R., "Introductions and Tables for Computing Potential Evapotranspiration and the Water Balance", Publications in Climatology. Laboratory of Climatology, Vol. X, No. 3, 1957, pp.181-311.

Thornthwaite, C.W.; Mather, J.R.; and Carter D.B., Three Water Balance Maps of Eastern North America. Resources for the Future, Washington D.C.: 1958.

Thornthwaite, C.W., and Associates, Average Climatic Water Balance Data of North America (excluding U.S.). Vol. 2, Part 6, Laboratory of Climatology, Centerton, N.J., 1964.

Thornthwaite, C.W., "The Moisture - Factor in Climate", Trans. Amer. Geophys, Union, Vol. 27, No. 1, 1967, pp.313-314.

Toogood, J.A., "Water Erosion in Alberta", Journal of Soil and Water Conservation; Vol. 18, pp.238-249, 1963.

Threwartha, G.F., An Introduction to Climate. New York, McGraw-Hill, 1968, 408p.

U.S. Army Corp of Engineers, Snow Hydrology. prepared by North Pacific Division, Portland, Oregon, 1956, 437p.

Van Wÿk, W.R. and De Vries, D.A., "Evapotranspiration", Netherlands Journal of Agricultural Science, Vol. 2, pp.105-119, 1954.

Verma, T.R., Moisture Balance in Soils of the Edmonton Area. Ph.D. thesis, Department of Soil Science, University of Alberta, 1968, 204p.

Walwyn, Stodgell and Co. Ltd., A Look at World Energy: The Athabasca Tar Sands. Toronto: 1973, p.51.

Ward, R.C., Principles of Hydrology. London: McGraw-Hill, 1967, 403p.

White, G.F., Strategies of American Water Management. Ann Arbor: The University of Michigan Press, 1969, 155p.

Wight, J.B., Aspects of Evaporation and Evapotranspiration in the Water Balance of Baker Creek Basin, Near Yellowknife, Northwest Territories. M.Sc. thesis, Department of Geography, University of Alberta, 1973, p.329.

Wilson, C.V., The Climate of Quebec - Energy Considerations. Ottawa: Information Canada, Climatological Studies no. 23, 1975, 120p.

Witter, S.G., The Mapping of Snow Patterns on the Cooking Lake Moraine Using Landsat I Imagery. M.Sc. thesis, Department of Geography, University of Alberta, 1976, 128p.

Woodburn, R., Water Balance Patterns in the Cooking Lake Moraine. M.Sc. thesis (in preparation), Department of Geography, University of Alberta, 1977.

APPENDIX I

Computer Program Using Penman Equation to Estimate Potential Evapotranspiration

The equation used to estimate potential evapotranspiration in the computer program is given by Penman (1963) to be:

$$E = \frac{{}^{\Delta}/\alpha \; H + Ea}{{}^{\Delta}/\alpha + x}$$

where E is the potential evapotranspiration, α is constant (= 0.62197) of the wet- and dry- bulb pshcrometer equa;tion, x is variable dependent on stomatal geometry and day-length and assumed equal to 1, and Δ is a related to the saturation vapor-pressure over water and temperature.

A heat budget equation, which is the dominant variable in the equation, is presented by Penman in the form:

$$H = R_i \; (1 - r) - R_b$$

where R_i is the short wave radiation,(r is the albedo crop coefficient assumed equal to .25 for the boreal forest), and R_b is the long radiation outward.

Since long-wave radiation measurements were unavailable an equation proposed by Penman was used for estimations:

$$R_b = \sigma \, T^4 \; (0.56 - 0.09 \, e_d^{\frac{1}{2}}) \; (0.10 + 0.90 \, {}^{n}/N)$$

where ${}^{n}/N$ is the ratio of actual to possible hours of sunshine, $\sigma \, T^4$ is the theoretical black-body radiation at mean air temperature (degrees Kelvin) expressed in evaporation equivalents, (equal to 1.98mm. H_2O/cm^2/ day $1°K^{4}$), and e_d is the mean vapor pressure of the atmosphere (mm.Hg).

Radiation data is converted from langleys to evaporation equivalent by dividing by the factor of 59(1mm. evaporation per day - 59 calories/ cm^2/day).

The drying power of the air (E_a) was estimated by the following equation:

$$E_a = 0.35\ (1 + {}^{U}/100)\ (e_w - e_d)$$

where U is the wind speed in miles per day taken at a height of two meters, e_w is the saturation vapor pressure at mean air temperature, and e_d is the mean vapor-pressure of the atmosphere.

To determine e_d, the values of e_w are needed and are given in the Smithsonian Meteorological Tables, however, it is easier to program these values. Values of e_d were then calculated as follows:

$$e_d = e_w \times \text{relative humidity}$$

where e_w is the saturation vapor-pressure over water. Pressure units have been expressed in millibars with an average barametric pressure of 935 m.b. used for the study area. For the most part, the equations presented and explanation were taken from an earlier thesis by Verma (1968).

The dimension statement of the program, lines 4 and 5, provide a listing of the input data used were:

TMAX = mean maximum monthly temperature in fahrenheit,

TMIN = mean minimum monthly temperature in fahrenheit,

RH05 = mean monthly relative humidity at 5 A.M.,

RH017 = mean monthly relative humidity at 5 P.M.,

WIND = mean wind speed in miles per hour,

RADIN = solar insolation received converted to evaporation equivalent,

```
C   GREGG WICHE
C   WORKING PENMAN EQUATION
C
      DIMENSION TMAX(30),TMIN(30),RHO5(30),RHO17(30),WIND(30),RADIN(30),
     8SUN(30),PTSUN(30),MO(30),YEAR(30)
      INTEGER*4 YEAR
      DOUBLE PRECISION EDAVE,WS,TST,SUN,PTSUN
      READ(11,50)K
   50 FORMAT(I2)
      DO 2 I=1,K
    2 READ(11,4)TMAX(I),TMIN(I),RHO5(I),RHO17(I),WIND(I),RADIN(I),SUN(I
     8),MO(I),YEAR(I),PTSUN(I)
    4 FORMAT(7F4.1,2I4,F6.2)
      WRITE(6,6)
    6 FORMAT('1',31X,'COMPUTATATION OF THE PENMAN EQUATION FOR ESTIMATIN
     3G EVAPOTRANSPIRATION')
      WRITE(6,1)
    1 FORMAT(' ',T20,'YEAR',T40,'MONTH',T60,'TMEAN',T80,'EVAPTRANSPIRATI
     9ON')
      DO 8 J=1,K
      ZRATIO=0.7239360793
      TMEAN=(TMAX(J)+TMIN(J))/2.0
      TCALC=((5.0/9.0)*(TMEAN-32.0))+273.16
      TEMP=TCALC
      TS=371.5
      WS=935.0
      TST=TS/TEMP
      PS1=(-7.90298*(TST-1.0))
      PS2=(5.02808*DLOG10(TST))
      PS3=0.0000001381 6*(10.0**(11.344*(1.0-TST))-1.0)
      PS4=0.00813218*(10.0**(-3.49149*(TST-1.0))-1.0)
      PS5=(PS1+PS2+PS4)-PS3
      PS=10.0**PS5
      EW=PS*WS
      EDAVE=EW*((RHO5(J)+RHO17(J))/2.0)
      DELTA1=EW/(TEMP**2.0)
      DELTA2=6790.5-(5.02808*TEMP)
      DELTA3=4916.8*(10.0**(-0.0304*TEMP))*(TEMP**2.0)
      DELTA4=17.4209-(1302.88/TEMP)
      DELTA=DELTA1*(DELTA2+DELTA3+DELTA4)
      RB=1.98D-9*(TEMP**4.0)*(0.56-(0.09*DSQRT(EDAVE)))*(.10+(.90*(SUN(J
     1)/PTSUN(J))))
      H=(RADIN(J)*0.75-RB)
      BUCALC=ZRATIO*WIND(J)
      EA=0.35*(1.0+(BUCALC/100.0))*((EW*0.75)-EDAVE)
      EP=((DELTA*H)+(0.62197*EA))/(DELTA+0.62197)
      I=MO(J)
      GO TO (21,20,21,21,20),I
   20 EP=EP*0.0394*30.0
      GO TO 25
   21 EP =EP*0.0394*31.0
   25 WRITE(6,12)YEAR(J),MO(J),TMEAN,EP
   12 FORMAT(' ',T20,I4,T40,I2,T60,F4.1,T80,F5.2)
    8 CONTINUE
      STOP
      END
```

SUN = mean daily maximum hours of possible sunlight,

FTSUN = mean daily actual sunlight received,

MO = number of the month,

YEAR = year of calculation.

Actual computation of the equation begins on line 21 with the ZRATIO being a scaling factor for the wind normally set equal to 1. Temperature is converted from degrees Fahrenheit to degrees Kelvin in lines 22 through 25. The Goff-Gratch (1946) formula is used in lines 28 through 35 to estimate e_w and e_d. Values of Δ at mean air temperature (TEMP) are computed in the equation presented in lines 35 through 40 where c_w is the saturation vapor-pressure over water. Component parts of the Penman equation are computed beginning on line 41 through 45, with the final computation taking place on line 46.

APPENDIX II

Comparison of Water Balance Techniques

Using Monthly and Daily Meteorological Data

Fort McMurray Alberta 1945 to 1975

Year	Potential Evapotranspiration		1.3 centimeter Surplus		1.3 centimeter Deficit	
	Daily	Monthly	Daily	Monthly	Daily	Monthly
1945	44.2	43.3	15.2	5.1	24.4	15.2
1946	49.4	48.2	9.1	6.4	24.3	18.4
1947	46.5	44.1	6.9	6.3	19.3	16.2
1948	51.0	52.0	6.7	2.5	31.9	30.9
1949	52.6	48.1	12.8	5.5	25.7	12.3
1950	47.2	44.9	25.5	13.9	30.7	24.1
1951	46.1	44.9	19.6	21.9	26.6	23.7
1952	53.2	53.3	7.3	11.8	25.7	24.8
1953	51.9	48.8	14.7	8.4	29.7	23.5
1954	50.2	47.9	20.6	13.2	23.5	12.5
1955	52.0	51.0	23.5	13.5	24.0	18.3
1956	50.1	48.7	25.2	21.9	22.0	13.7
1957	47.9	47.3	16.5	11.4	18.1	15.5
1958	50.1	50.7	22.0	16.5	31.7	23.5
1959	43.2	42.6	24.7	17.5	16.4	8.9
1960	49.7	49.1	32.6	15.7	22.4	6.4
1961	51.8	48.9	23.0	14.8	33.9	25.4
1962	49.5	47.7	25.6	16.1	18.6	7.3

Appendix II - continued

Year	Potential Evapotranspiration Daily	Potential Evapotranspiration Monthly	1.3 centimeter Surplus Daily	1.3 centimeter Surplus Monthly	1.3 centimeter Deficit Daily	1.3 centimeter Deficit Monthly
1963	55.0	55.7	8.1	6.9	30.9	30.3
1964	54.0	52.9	8.2	7.3	24.4	22.6
1965	50.0	50.8	13.3	8.3	24.7	22.2
1966	49.8	49.1	26.9	15.6	24.6	16.4
1967	50.1	48.7	21.3	16.4	10.8	18.1
1968	48.2	47.0	16.3	10.9	18.2	12.9
1969	49.8	49.1	28.0	23.1	25.8	19.5
1970	52.7	52.2	27.1	17.6	22.6	11.0
1971	54.1	55.6	13.6	8.8	35.5	29.9
1972	49.0	46.3	32.6	27.5	24.5	19.5
1973	54.1	53.9	33.0	18.6	19.1	4.3
1974	49.9	48.7	13.0	8.7	18.6	13.1
1975	52.2	51.8	22.0	13.1	14.8	7.4
1976	58.2	56.3	9.9	12.5	24.0	19.1
Average	50.1	49.1	18.9	13.1	24.4	17.7

Appendix II - continued

Year	5 centimeter storage (surplus) Daily	Monthly	5 centimeter storage (deficit) Daily	Monthly
1945	2.8	1.3	14.0	11.4
1946	3.7	2.6	16.2	14.6
1947	28.2	2.4	14.1	12.4
1948	23.3	1.8	26.5	25.3
1949	4.9	1.7	14.7	8.5
1950	18.6	8.9	25.0	20.2
1951	13.5	19.3	20.5	19.9
1952	5.4	8.0	20.3	21.0
1953	2.7	4.6	21.3	19.7
1954	8.8	8.9	9.4	8.2
1955	14.6	9.7	17.3	14.5
1956	16.3	13.1	13.1	8.6
1957	9.7	7.6	12.5	11.7
1958	13.2	16.5	23.0	19.7
1959	15.9	9.9	6.8	5.1
1960	20.3	14.8	10.1	2.6
1961	13.9	11.8	24.8	21.5
1962	14.5	12.2	7.5	3.4
1963	5.7	5.1	26.4	26.5
1964	2.9	3.5	19.5	18.8
1965	5.1	4.4	18.4	18.4

Appendix II - continued

Year	5 centimeter storage (surplus) Daily	Monthly	5 centimeter storage (deficit) Daily	Monthly
1966	14.4	9.3	12.1	12.6
1967	9.7	14.7	15.8	13.9
1968	9.9	4.6	11.7	9.0
1969	19.5	18.0	17.3	15.7
1970	12.6	13.8	8.0	7.2
1971	7.6	8.8	26.7	26.1
1972	26.3	19.9	18.2	15.7
1973	17.9	14.8	3.9	.5
1974	7.6	6.8	11.3	9.1
1975	11.5	5.5	6.2	3.6
1976	6.7	5.9	13.4	12.4
Average	10.5	9.1	15.8	13.7

Appendix II - continued

Year	10 centimeter storage (surplus) Daily	Monthly	10 centimeter storage (deficit) Daily	Monthly
1945	0.	0.	12.1	10.1
1946	.3	0.	10.6	11.9
1947	0.	0.	12.3	10.2
1948	0.	0.	25.0	27.1
1949	0.	0.	14.4	6.7
1950	8.5	3.8	19.9	15.2
1951	11.3	14.2	15.6	14.8
1952	2.7	2.9	15.2	15.9
1953	0.	0.	19.5	15.1
1954	4.4	3.9	4.4	3.2
1955	4.4	4.6	12.2	9.4
1956	8.1	7.6	4.9	3.5
1957	4.6	2.3	6.2	6.6
1958	9.0	12.0	15.4	14.6
1959	7.2	2.5	1.7	.1
1960	14.6	12.1	4.4	0.
1961	8.6	9.1	19.3	16.5
1962	11.2	9.3	2.5	0.
1963	3.9	2.9	21.3	21.4
1964	0.	0.	16.6	15.2
1965	0.	0.	14.0	13.9

Appendix II - continued

	10 centimeter storage (surplus)		10 centimeter storage (deficit)	
	Daily	Monthly	Daily	Monthly
1966	5.0	4.2	7.0	7.5
1967	8.2	9.7	10.7	8.8
1968	1.2	0.	6.7	4.4
1969	14.4	7.9	12.2	10.6
1970	7.3	11.0	2.7	2.2
1971	6.6	6.5	21.6	21.1
1972	17.2	10.6	13.2	10.6
1973	13.9	13.4	0.	0.
1974	7.6	6.8	6.2	4.2
1975	2.4	0.	2.3	.0
1976	9.9	5.1	8.4	7.3
Average	6.0	5.1	11.2	9.6

Appendix II - continued

Year	15 centimeter storage (surplus) Daily	Monthly	15 centimeter storage (deficit) Daily	Monthly
1945	0.	0.	12.1	10.1
1946	0.	0.	10.3	11.9
1947	0.	0.	12.3	10.2
1948	0.	0.	25.0	27.1
1949	0.	0.	14.4	6.7
1950	0.	0.	16.5	11.3
1951	11.2	9.1	10.6	9.7
1952	0.	0.	12.5	12.9
1953	0.	0.	19.5	15.1
1954	0.	0.	0.	0.
1955	0.	.2	8.0	4.3
1956	3.6	2.5	0.	0.
1957	0.	0.	3.0	2.8
1958	3.6	6.9	7.7	9.5
1959	.5	0.	0.	0.
1960	10.2	9.4	0.	0.
1961	7.5	9.1	14.5	11.4
1962	7.0	4.2	0.	0.
1963	.9	2.9	15.2	16.3
1964	0.	0.	16.6	14.7
1965	0.	0.	14.0	13.9

Appendix II - continued

Year	15 centimeter storage (surplus) Daily	Monthly	15 centimeter storage (deficit) Daily	Monthly
1966	0.	0.	3.5	3.3
1967	4.6	4.6	5.6	3.7
1968	0.	0.	5.6	4.4
1969	4.5	.8	7.1	5.5
1970	6.1	7.9	0.	0.
1971	5.0	4.3	16.5	16.0
1972	7.0	5.5	8.1	5.6
1973	13.9	13.4	0.	0.
1974	7.6	6.8	1.1	0.
1975	0.	0.	2.3	0.
1976	2.5	1.7	3.3	2.3
Average	3.0	2.8	8.4	7.3

Appendix II - continued

Year	25 centimeter storage (surplus) Daily	Monthly	25 centimeter storage (deficit) Daily	Monthly
1945	0.	0.	12.1	10.1
1946	0.	0.	10.3	11.9
1947	0.	0.	12.3	10.2
1948	0.	0.	25.0	27.1
1949	0.	0.	14.4	6.7
1950	0.	0.	16.5	11.3
1951	1.0	0.	.4	.6
1952	0.	0.	12.5	12.9
1953	0.	0.	19.5	15.1
1954	0.	0.	0.	0.
1955	0.	0.	8.0	4.0
1956	0.	0.	0.	0.
1957	0.	0.	0.	.2
1958	0.	0.	4.1	2.5
1959	0.	0.	0.	0.
1960	.6	0.	0.	0.
1961	8.2	8.5	4.3	1.2
1962	0.	0.	0.	0.
1963	0.	0.	7.6	7.6
1964	0.	0.	16.6	15.2
1965	0.	0.	14.0	13.9

Appendix II - continued

Year	25 centimeter storage (surplus) Daily	Monthly	25 centimeter storage (deficit) Daily	Monthly
1966	0.	0.	3.5	3.3
1967	0.	0.	.9	0.
1968	0.	0.	5.7	3.6
1969	0.	0.	5.3	4.6
1970	0.	0.	0.	0.
1971	3.6	2.0	6.4	5.8
1972	0.	0.	2.8	0.
1973	5.6	0.	0.	0.
1974	7.6	6.8	0.	0.
1975	0.	0.	0.	0.
1976	0.	0.	0.	0.
Average	.8	.5	6.5	5.3

Appendix III: Monthly Water Balance - 1972 - Using Thornthwaite Procedures*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-26.0	-22.1	-7.1	-0.6	11.9	15.2	14.2	16.7	3.7	0.2	-8.1	- 21.3	
	PE	-	-	-	-	9.1	11.4	10.4	11.4	3.2	.7	-	-	46.2
	Ppt.	3.2	4.7	3.0	4.2	1.6	7.5	7.0	5.3	6.5	6.6	4.2	2.6	56.4
	S.C.	3.2	4.7	3.0	4.2	7.5	3.9	-3.4	-6.1	3.3	5.9	4.2	2.6	
1.3	St.	.5	.5	.5	.5	-	-	-	-	.5	.5	.5	.5	
1.3	Surp.	3.2	4.7	3.0	4.2	-	-	-	-	2.8	5.9	4.2	2.6	30.6
	Def.	-	-	-	-	7.0	3.9	3.4	6.1	-	-	-	-	20.4
5	St.	5.	5.	5.	5.	0	-	-	-	3.3	5.	5.	5.	
5	Surp	3.2	4.7	3.0	4.2	-	-	-	-	-	4.2	4.2	2.6	2.61
	Def.	-	-	-	-	2.5	3.9	3.4	6.1	-	-	-	-	15.9
10	St.	8.6	10.	10.	10.	2.5	-	-	-	3.3	9.2	10.	10.	
5.4	Surp		3.3	3.0	4.2	-	-	-	-	-	-	3.4	2.6	16.5
	Def.	-	-	-	-	-	2.4	3.4	6.1	-	-	-	-	11.9
15	St.	8.6	13.3	15.	15.	7.5	3.6	.2	-	3.3	9.2	13.4	15.	
5.4	Surp.	-	-	1.3	4.2	-	-	-	-	-	-	-	1.0	6.5
	Def.	-	-	-	-	-	-	-	5.9					5.9
25	St.	8.6	13.3	16.3	20.5	13.0	9.1	5.7	0	3.3	9.2	13.4	16.0	
5.4	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	15.1
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	.4

*Data taken from Fort McMurray Meteorological Station

Appendix III: Monthly Water Balance - 1973 - Using Thornthwaite Procedures*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-16.3	-14.9	-2.8	3.0	12.8	14.5	17.0	15.0	9.6	3.3	-14.0	-19.5	
	PE	-	-	-	2.6	9.1	11.4	12.5	10.4	5.6	2.1	-	-	53.7
	Ppt.	4.3	1.6	.4	1.1	5.6	10.7	13.7	12.4	5.8	5.4	4.2	1.9	67.1
	S.C.	4.3	1.6	.4	-1.5	-3.5	-.7	1.2	2.0	.2	3.3	4.2	1.9	
1.3	St.	.5	.5	.5	-	-	-	.5	.5	.5	.5	.5	.5	
1.3	Surp.	4.3	1.6	.4	-	-	-	.7	2.0	.2	3.3	4.2	1.9	18.6
	Def.	-	-	-	1.0	3.5	.7	-	-	-	-	-	-	5.2
5	St.	5.	5.	5.	3.5	-	-	1.2	3.2	3.4	5.	5.	5.	
5	Surp.	4.3	1.6	.4	-	-	-	-	-	-	1.7	4.2	1.9	14.1
	Def.	-	-	-	-	-	.7							.7
10	St.	10.	10.	10.	8.5	5.0	4.3	5.5	7.5	7.7	10.	10.	10.	
10	Surp.	4.3	1.6	.4	-	-	-	-	-	-	1.	4.2	1.9	13.4
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
15	St.	15.	15.	15.	13.5	10.0	9.3	10.5	12.5	12.7	15.0	15.0	15.0	
15	Surp.	4.3	1.6	.4	-	-	-	-	-	-	1.0	4.2	1.9	13.4
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
25	St.	20.3	21.9	22.3	20.8	17.3	16.6	17.8	19.9	21.1	24.4	25.	25.0	
16	Surp	-	-	-	-	-	-	-	-	-	-	3.8	1.9	5.7
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

*Data taken from Fort McMurray Meteorological Station

Appendix III: Monthly Water Balance - 1974 - Using Thornthwaite Procedures*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-24.5	-14.9	-14.0	3.4	7.2	14.9	15.7	13.0	7.6	4.2	-4.5	-9.3	
	PE	-	-	-	2.6	6.0	11.4	11.4	9.5	4.8	2.7	-	-	48.4
	Ppt.	3.2	1.8	1.8	1.2	3.8	7.1	10.8	6.7	3.3	1.1	1.2	1.8	43.8
	S.C.	3.2	1.8	1.8	-1.4	-2.2	-4.3	-.6	-2.8	-1.5	-1.6	1.2	1.8	
1.3	St.	.5	.5	.5	-	-	-	-	-	-	-	.5	.5	
1.3	Surp.	3.2	1.8	1.8	-	-	-	-	-	-	-	.7	1.8	9.3
	Def.	-	-	-	-.9	2.2	4.3	.6	2.8	1.5	1.6	-	-	13.9
5.	St.	5.	5.	5.	3.6	1.4	2.9	2.3	-	-	-	1.2	3.0	
5.0	Surp.	3.2	1.8	1.8	-	-	-	-	-	-	-	-	-	6.8
	Def.	-	-	-	-	-	-	-	.5	1.5	1.6	-	-	3.6
10.	St.	10.	10.	10.	8.6	6.4	2.1	1.5	-	-	-	1.2	3.0	
10.0	Surp.	3.2	1.8	1.8	-	-	-	-	-	-	-	-	-	6.8
	Def.	-	-	-	-	-	-	-	1.3	1.5	1.6	-	-	4.4
15.	St.	15.	15.	15.	13.6	11.4	7.1	6.5	3.7	2.2	.6	1.8	3.6	
15.0	Surp.	3.2	1.8	1.8	-	-	-	-	-	-	-	-	-	6.8
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
25.	St.	25.	25.	25.	23.6	21.4	17.1	16.5	13.7	12.2	10.6	11.8	13.6	
25.0	Surp.	3.2	1.8	1.8	-	-	-	-	-	-	-	-	-	6.8
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

*Data taken from Fort McMurray Meteorological Station

Appendix III: Monthly Water Balance - 1975 - Using Thornthwaite Procedures*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-19.2	-16.4	-9.6	1.7	9.6	13.9	18.0	13.0	10.0	3.1	-8.3	-18.9	
	PE	-	-	-	1.7	8.1	10.3	13.5	9.5	6.4	2.1	-	-	51.6
	Ppt.	2.5	.7	1.6	2.8	7.0	9.0	7.1	11.9	9.0	3.5	1.4	2.6	59.1
	S.C.	2.5	.7	1.6	1.1	-1.1	-1.3	-6.4	2.4	2.6	1.4	1.4	2.6	
1.3	St.	.5	.5	.5	.5	-	-	-	.5	.5	.5	.5	.5	
1.3	Surp.	2.5	.7	1.6	1.1	-	-	-	1.9	2.6	1.4	1.4	2.6	15.8
	Def.	-	-	-	-	.6	1.3	6.4	-	-	-	-	-	8.3
5.	St.	5.	5.	5.	5.	3.9	2.6	-	2.4	5.0	5.0	5.0	5.0	
3.0	Surp.	.5	.7	1.6	1.1	-	-	-	-	-	1.4	1.4	2.6	9.3
	Def.	-	-	-	-	-	-	3.8	-	-	-	-	-	3.8
10.	St.	5.5	6.2	7.8	8.9	7.8	6.5	0.1	2.5	5.1	6.5	7.9	10.	
3.0	Surp.	-	-	-	-	-	-	-	-	-	-	-	.5	.5
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
15.	St.	6.1	6.8	8.4	9.5	8.4	7.1	10.7	3.1	5.7	7.1	8.5	11.1	
3.6	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	
25.	St.	16.1	16.8	18.4	19.5	18.4	17.1	10.7	13.1	15.7	17.1	18.5	21.1	
13.6	Surp.	-	-	-	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

*Data taken from Fort McMurray Meteorological Station

Appendix III: Monthly Water Balance - 1976 - Using Thornthwaite Procedures*

		J	F	M	A	M	J	J	A	S	O	N	D	Year
	°C	-16.6	-14.9	-8.5	7.1	11.5	14.2	16.5	16.3	12.1	1.8	-4.9	-17.0	
	PE	-	-	-	5.2	8.1	10.3	12.5	11.4	7.2	1.3	-	-	56.0
	Ppt.	1.3	2.9	0.8	0.6	2.2	4.2	11.4	17.3	3.1	4.5	0.8	1.6	50.7
	S.C.	1.3	2.9	0.8	-4.6	-5.9	-6.1	-1.1	5.9	-4.1	3.2	0.8	1.6	
1.3	St.	.5	.5	.5	-	-	-	-	.5	-	.5	-	-	
.5	Surp.	1.3	2.9	0.8	-	-	-	-	5.4	-	2.7	0.8	1.6	15.5
	Def.	-	-	-	4.1	5.9	6.1	1.1	-	3.6	-	-	-	20.8
5.	St.	5.	5.	5.	.4	-	-	-	5.0	.9	4.1	4.9	5.0	
5.	Surp.	1.3	2.9	0.8	-	-	-	-	.9	-	-	-	1.5	7.4
	Def.	-	-	-	-	5.5	6.1	1.1	-	-	-	-	-	12.7
10.	St.	10.	10.	10.	5.4	-	-	-	5.9	1.8	5.0	5.8	7.4	
10.	Surp.	1.3	2.9	0.8	-	-	-	-	-	-	-	-	-	5.0
	Def.	-	-	-	-	0.5	6.1	1.1	-	-	-	-	-	7.7
15.	St.	12.4	15.3	11.5	10.7	4.8	-	-	5.9	1.8	5.0	5.8	7.4	
11.1	Surp.	-	-	1.1	-	-	-	-	-	-	-	-	-	
	Def.	-	-	-	-	-	1.3	-1.1	-	-	-	-	-	2.4
25.	St.	22.4	25.	25.	20.4	14.5	8.4	7.3	13.2	9.1	12.3	13.1	14.7	
21.1	Surp.	-	.3	0.8	-	-	-	-	-	-	-	-	-	1.1
	Def.	-	-	-	-	-	-	-	-	-	-	-	-	

*Data taken from Fort McMurray Meteorological Station

APPENDIX IV

Net Evaporation from Open Water Using Monthly Water Balance Procedures

Year	Net Evaporation (cm)	Year	Net Evaporation (cm)
1949	-11.7	1963	-34.1
1950	-10.5	1964	-22.7
1951	-13.2	1965	-19.2
1952	-26.4	1966	- .7
1953	-19.8	1967	- 9.1
1954	- 2.1	1968	- 2.8
1955	- 4.1	1969	- 2.4
1956	+ 2.7	1970	+ 3.9
1957	- 4.2	1971	-31.2
1958	-17.7	1972	+ 5.4
1959	+ 9.6	1973	+13.5
1960	+10.7	1974	- 6.4
1961	-11.2	1975	+ 7.8
1962	6.8	1976	- 7.9